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[*Continued on page (III) of Cover.*

19 FEB 1965

FLUID FILLING-MEDIA FOR ELECTRICAL APPARATUS

By F. MEYER, B.Sc.*

(*Paper first received* 30*th January, and in revised form* 30*th September*, 1939. *The paper would have been read and discussed before* THE INSTITUTION *on the* 23*rd November*, 1939, *but the meeting was cancelled owing to the war*.)

SUMMARY

It is the object of the author in this paper to discuss the common fluid filling-media for electrical apparatus, particularly transformers, and to advance suggestions as to the improvement of British Standard Specification 148—1933 (" Insulating Oils for Electrical Purposes "). In addition, the properties of chlorinated diphenyls are discussed and also the particular requirements of oils suitable for condensers. For the sake of clarity, the paper is divided into three headings:—

(1) Transformer and switch oils.
(2) Chlorinated compounds.
(3) Condenser oils.

(1) TRANSFORMER AND SWITCH OILS

General

When oil was first adopted for filling transformers and switchgear, use was naturally made of the most suitable existing kind of oil. Even 30 years ago full approval was accorded to oils that would be instantly rejected to-day, not only with regard to their electrical properties but also to their physical characteristics. With the advent of the first B.S. Specification for insulating oil, however, in 1923, standard methods of test were evolved and specification limits laid down which have gradually led to the improvement of electrical oils, so that in 1927, and again in 1933, B.S. Specification 148 was able to be revised and tightened up, with the result that oil manufacturers continued to improve their product until, to-day, electrical insulating oil to B.S. Specification 148—1933 could be safely used medicinally, so far has the degree of refining been carried.

In some ways, perhaps unfortunately, the classification of oils was adopted on a basis of sludge values taken by a method far removed from service conditions. The cry of the transformer manufacturers then was for as low sludge values as possible, and the criterion of a good transformer oil became a low sludge value, without very much attention being paid to its other properties. This attitude has led oil refiners to develop insulating oils mainly in one direction, and it has become evident that, through curing the development of sludge in an oil by a high degree of refinement, transformer oils of to-day develop acidity instead. The Michie test for sludge, therefore, instead of being used to eradicate unsuitable oils, became the basis of comparison for oils in that the lowest sludge-value oil was adjudged the most suitable. What the Michie sludge test for oil determines as to its suitability for use in a transformer, except as a proof test, is difficult to see, as it does not measure anything in relation to service conditions and is not a true ageing test by acceleration. It is a well-known fact that the oxidation products of an oil at 150° C. are far different from those taken at 90° C., both in quantity and in character. The Michie test has outgrown its original use as a test for the eradication of unsuitable oils.

It is safe to say that 50 % of the transformer oil used to-day is Class A oil, typical samples of which give practically zero sludge values. For switchgear purposes, where sludge is of small importance, highly refined oil is quite unnecessary. It follows also that oil would be cheaper if less refined, a point of importance considering the large bulk of oil used. Class B oils, which years ago were just attainable with sludge values between 0·7 and 0·8, are nowadays readily procurable at the low figure of 0·3 and less. It is the author's contention that in bringing the sludge values of oils down to these low limits, the danger of development of acidity of oils is now as menacing as the old danger of high sludge values. It may well be that in the light of modern experience with transformer oils, the highly refined Class A oils of practically zero sludge value employed so widely to-day will be discarded and an oil of a moderate degree of refinement but low developed acidity will take its place as standard transformer oil.

Experience and Tests

It has been the author's experience from time to time to open up transformers which have been in service, and it has been noticed that the underside of the lid has been corroded, the amount of corrosion being far in excess of what one would expect through ordinary rusting. An analysis of this corrosive deposit has revealed the presence of acetic acid due to the development of volatile acidity by the oil. In addition to this, the acid value of the oil itself has been far in excess of its original value, reaching as high in some cases as 4–5 milligrammes of KOH per gramme of oil, as against an original acid value of approximately 0·05 milligramme KOH. The following is an account of an investigation undertaken to obtain some idea of:—

(*a*) The rate of development of acidity under a given set of conditions approximating to ordinary service transformer duty.

(*b*) The effect on acid development of varnished and unvarnished coils.

(*c*) The difference in development of acidity between oils supplied by different manufacturers.

(*d*) The difference in development of acidity between Class A and Class B oils.

The details of the test apparatus are shown in Fig. 1.

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* General Electric Company, Ltd.

Coils were made up as follows, using 20 S.W.G., double-cotton-covered wire:—

Internal diameter	2 in.
External diameter	3 in.
Width of coil	2 in.

For the test, these were supported on bakelized-paper supports (A) inside ordinary sheet-iron tins (B) of approximately 1½ gallons capacity, fitted with lever type lids. The two ends (C) of the coil were taken through small holes in the lid of the container, and in each case a thermometer (D) was fitted through the lid so as to have its bulb centrally disposed with reference to the coil. For four of the oil samples (two Class A and two Class B) two tins each were prepared, one tin containing a standard coil untreated except for drying for 18 hours at 100° C., and the other containing a standard coil, varnish-impregnated with a yellow-oil-base insulating varnish.

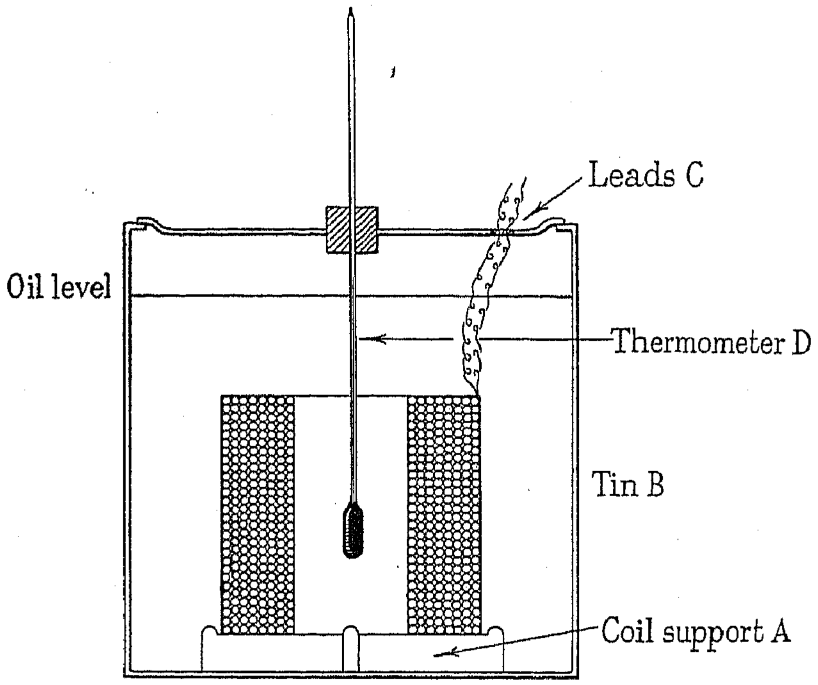

Fig. 1

For the rest of the oil samples, impregnated coils only were used.

The coils were connected to an a.c. supply such as to give a steady condition of temperature of 85°–90° C. as read on each thermometer, and the test was carried on continuously for 6 months (except for an occasional week-end shutdown). The acid value of the oil in each tin was taken at the end of each month, the samples for test being extracted through the thermometer holes. These results are set out in Table 1. At the end of 6 months each tin was opened and the inside conditions were noted (see Table 2). In addition, the average developed acidity for the Class A oils against the Class B oils is shown in Fig. 2.

Conclusions Drawn from Investigation

Taking general tendencies as given by this investigation, the answers to the points set out to determine are:—

(*a*) For the Class A oils, there seems to be a definite acceleration in formation of acid during the third month, and even after 6 months there is no evident tendency to decrease the rate; in fact the average curve indicates an increasing rate of acid formation at 6 months.

With regard to the Class B oils the rate of rise over the 6 months is fairly uniform, with definite indications that the rate of formation of acid is decreasing after approximately 5 months.

(*b*) The " A " oils containing varnished coils developed slightly more acid than the corresponding oils containing unvarnished coils. An examination of Table 2 shows, however, that the lids of the tins in the former cases were free from rusting, but were rusted in the latter case. This would seem to indicate that more volatile acidity was developed in the case of unvarnished coils. The Class B oils containing varnished coils developed less acidity than the corresponding oils containing unvarnished coils and, judging by the state of the tin lids, very little or no volatile acidity was developed at all.

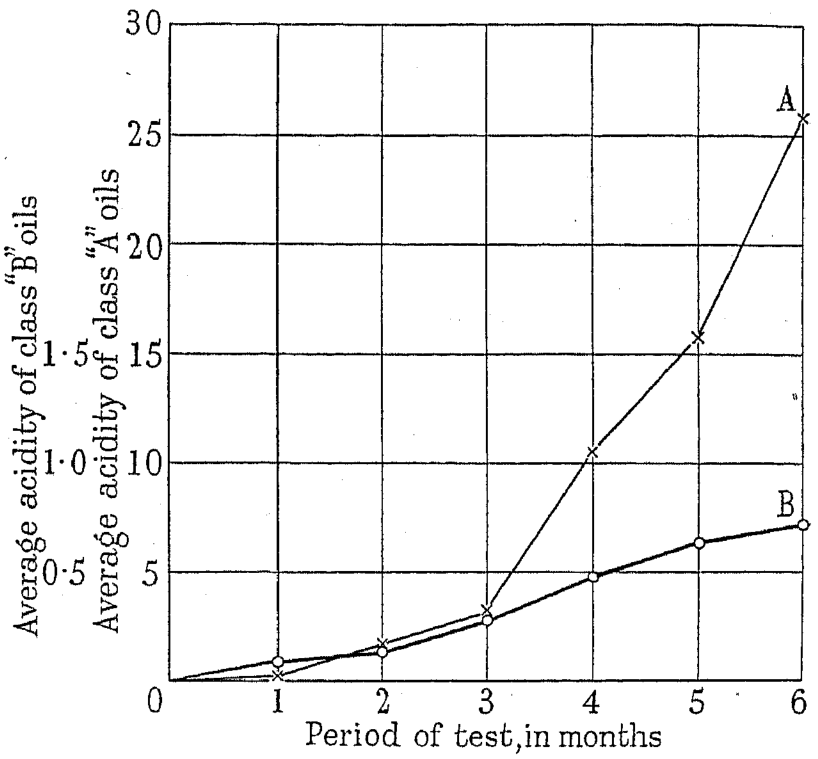

Fig. 2.—Curves showing average development of acidity of Class A and Class B oils over a test period of 6 months. Acidity figures in milligrammes KOH per gramme of oil.

× × Class A oils. ○ ○ Class B oils.

(*c*) Generally speaking, there was little difference shown between the various Class A oils, and although more relative difference was shown between the various Class B oils the worst measured acidity developed was, in actual terms, small in comparison with the Class A results.

(*d*) The difference in developed acidity between the Class A and Class B oils is very marked, with the less acidity in decided favour of the Class B.

Proposals

Taking into consideration this investigation and also the sum total of the experience of transformer-oil users, the author considers that a strong case has been made for the adoption of an oil of the lowest acidity development, even at the expense of the low sludge values now obtained. The next point to arise, however, is this: How is the development of acidity to be measured? Seeing that the Michie sludge test is the standard British ageing method for oils, the logical proposal would seem to be to carry it a step further and use it for measuring developed acidity as well as sludge.

It has been found that if, after separating out the sludge, the acid value of the remaining liquor be determined, the normal Class B oil gives a value of 3–4 milligrammes of KOH per gramme of oil. This acid value corresponds to values obtained in the test previously described after 3–4 months (with unvarnished coils) and would, therefore, seem a suitable test which could easily be included in a specification. The next logical step is, that if a Class B oil of sludge value 0·2–0·3 develops less acidity than a Class A oil of practically zero sludge value, it is logical to assume that, using the same base oil but of a less degree of refinement, say with a sludge of 0·4–0·6, the latter oil ought to develop still less acidity. In conjunction with a well-known oil supplier, this supposition has been checked with the excellent result that an oil was produced with an acidity developed figure, taken after the standard Michie sludge test, of 0·96 milligramme KOH and a sludge value of 0·46 %. This sludge value is well within the maximum B.S.S. 148—1933 figure of 0·8 %, and such an oil should not develop an undue amount of sludge under the severest service conditions, nor should it develop much acidity in service.

Table 1(A)

ACIDITY DEVELOPMENT OF CLASS A OILS (IN MILLIGRAMMES KOH PER GRAMME OF OIL)

Sample	Varnished coils						Unvarnished coils					
Ref.	1 month	2 months	3 months	4 months	5 months	6 months	1 month	2 months	3 months	4 months	5 months	6 months
A	0·028	0·11	4·09	11·0	16·6	27·7	0·14	0·182	5·0	8·75	12·3	16·0
B	0·028	0·42	5·01	12·2	17·5	26·8	0·02	0·42	5·49	7·4	16·4	22·3
C	0·02	0·07	1·90	9·1	14·3	23·7						
D	0·014	0·07	1·81	9·5	14·8	25·5						
Average	0·023	0·17	2·6	10·5	15·8	25·9						

Table 1(B)

ACIDITY DEVELOPMENT OF CLASS B OILS (IN MILLIGRAMMES KOH PER GRAMME OF OIL)

Sample	Varnished coils						Unvarnished coils					
Ref.	1 month	2 months	3 months	4 months	5 months	6 months	1 month	2 months	3 months	4 months	5 months	6 months
A	0·028	0·07	0·37	0·39	0·58	0·55	0·063	0·435	1·39	2·38	2.52	3·2
B	0·042	0·168	0·42	0·85	1·25	1·4	0·05	0·084	5·6	9·4	10·2	12·6
C	0·112	0·12	0·14	0·16	0·196	0·28						
D	0·028	0·08	0·42	0·83	0·86	0·91						
E	0·169	0·18	0·196	0·25	0·33	0·40						
Average	0·076	0·124	0·309	0·49	0·633	0·71						

The way in which the degree of refining influences the character of the oxidation products may be explained by the resins in the partially refined oil being oxidized to a solid substance, i.e. sludge, and that these products in some way prevent the oxidation of the hydrocarbon portions. In the case of highly refined oils there is no protection of the hydrocarbon portions by polymerization products, it being assumed that direct oxidation of the hydrocarbons produces acidity.

It is also logical to assume that the composition of the actual crude oil itself plays a large part in the determination of the properties of the refined oil.

Table 2

CONDITION OF OILS AFTER SIX MONTHS

Sample Ref.	Class	V—coil varnished UV—coil unvarnished	Electric strength of oil—breakdown voltage/(seconds for breakdown)	Colour of oil	Amount of deposit in oil	Colour of deposit in oil	Deposit on sides of tin	Deposit on lid of tin	Amount of deposit on coil	Colour of deposit on coil	Nature of deposit on coil	Moisture in oil* (by "crackle" test)
A	A	UV	21 000 volts 28 000 volts 25 000 volts Instantaneously in each case	Very dark brown	Copious	Dark brown	Slight amount, dark brown, sticky	Large amount, dark brown, rusty and gummy	Copious	Dark brown	Slimy	III
A	A	V	30 000/2 30 000/5 30 000/5	Light yellow	None	—	Very slight amount, light yellow, sticky	None	Copious	Dark greenish brown	Sticky	II
B	A	UV	30 000/40 30 000/20 30 000/25	Dark brown	Slightly clouded	Whitish	Slight amount, yellow, sticky	Slightly rusted	Copious	Greenish brown	Soft	II
B	A	V	30 000/6 30 000/5 30 000/11	Light yellow	None	—	Slight amount, yellow, sticky	None	Copious	Dark green	Slimy	II
C	A	V	30 000/60 no breakdown. Breakdown at 35 000	Light yellow	None	—	Slight amount, white, soft	None	Slight	Dark greenish brown	Soft, gritty	I
D	A	V	30 000/60 no breakdown. Breakdown at 4 000	Light yellow	None	—	Slight amount, colourless, soft	None	Slight amount in blobs	Light greenish brown	Sticky	I
A	B	UV	30 000/20 30 000/10 30 000/25	Light yellow	None	—	Very slight amount, white, sticky	Very slight rusting	Slight	Dark greenish brown	Soft	II
A	B	V	16 000 volts 12 000 volts 14 000 volts Instantaneously	Dark brown	Fairly copious	Dark brown	Slight amount, dark brown	None	Copious	Dark brown	Soft	II
B	B	UV	30 000/8 30 000/4 30 000/6	Dark brown	Slight	—	Fairly thick, reddish brown, sticky	Slight rusting	Copious	White	Sticky	II
B	B	V	20 000 volts 25 000 volts 22 000 volts Instantaneously	Dark brown	Slight	—	Fairly thick, dark brown, soft	None	Copious	Dark brown	Soft	II
C	B	V	30 000/5 27 000 30 000/11	Light reddish brown	Slight	Light yellow	Yellow, soft	None	Slight	Yellow	Soft	I
D	B	V	30 000/2 30 000/5 30 000/5	Light brown	Slight	—	Slight amount, dark brown, sticky	None	Very slight	Light yellow	Soft	II
E	B	V	15 000 volts 11 000 volts 12 000 volts	Light brown	Slight	—	Slight amount, light brown, soft	None	None	None	—	II

* I—None. II—Slight trace. III—Trace.

The method of refining is also said to have a large bearing on the characteristics of the refined oil. It is considered in some quarters that methods of refining which remove all the aromatic unsaturated molecules produce insulating oils which easily form acids in service, whereas by removing all unsaturated aliphatic constituents an oil of low acidity formation is produced.

It thus appears that the following factors all influence to some degree the formation of acid in an oil under service conditions:—

(1) Origin of crude oil and its characteristics.
(2) Method of treatment of crude oil to produce basic transformer-oil distillate.
(3) Method of refining blended basic oil distillate.
(4) Degree of refining.

The investigation of these variables provides much scope for the enterprising oil supplier.

Suggestions for Test and Specification Purposes

In the treatment of acidity development of oil in this paper, little mention has so far been made of volatile acidity, the results of which are usually shown more plainly in transformers than residual acidity in the body of the oil, as it produces corrosion of metal parts above oil level. The Michie sludge test would tend to carry over volatile acidity unless condensed in a special trap, so that the measurement of the acidity of the sludge liquor does not necessarily tell a complete story. So far as the limited experience of the author on this particular point is concerned, it appears reasonable to assume that if steps are taken to keep down residual developed acidity, then volatile acidity will also be reduced. In any case, the provision of breathers on transformers has been found to reduce corrosion through volatile acidity, although it is not known if this step prevents its formation or merely gets rid of it before it has time to do damage.

B.S.S. 148—1933 is considered inadequate on two points, therefore, in that:—

(*a*) The sludge test bears no relation to service conditions unless a relationship between deposit at 150° C. and, say, 110° C., is established.

(*b*) No mention is made of developed acidity after ageing.

The remedy for the former is either to determine the relationship mentioned, substitute a sludge test at 110° C. for a longer period, or substitute a sludge test at 110° C. for the same period and reduce the specification limit. The remedy for the latter is, of course, to measure and specify a limit for the developed acidity after the sludge test.

The following method has been found efficacious for the determination of developed acidity after sludging:—

> Filter off the sludge and make up the filtrate by addition of petroleum ether to 500 cm^3 Take 200 cm^3 of this, add 100 cm^3 of neutral alcohol with 2 cm^3 of alkali blue indicator, and allow to stand for 24 hours. Titrate with N/10 KOH.

Using this method, the author considers it feasible to fix a maximum developed acidity of 1·5 milligrammes KOH.

(2) CHLORINATED COMPOUNDS

Introduction

The greatest drawback of oil as a filling medium is its inflammability, and in consequence of such disastrous switchgear and transformer fires as those at Bradford and Kingston-on-Thames, and the danger of fires caused by incendiary bombs, the thoughts of engineers are strongly turned towards the only non-inflammable liquids at present commercially available, i.e. synthetic chlorinated compounds. The commonest of these are the chlorinated diphenyls made in America and on the Continent, but not so far manufactured in this country.

Chlorinated Naphthalenes

The drawback to the use of these for filling electrical apparatus is that there is considerable doubt as to their stability under heat, in the liquid form. The author has found that the liquid variety tends to evolve chlorine at temperatures of approximately 100°–110° C. and on this account little use has been made of them, except possibly for liquid fuses. In the solid form, better known as the Seekay waxes, they have been used in the electrical industry, to a limited extent, as a non-inflammable filling compound in place of bitumen and other waxes.

Chlorinated Diphenyls

It is a well-known fact that there have been marketed in America for some years now types of transformers filled with non-inflammable liquids known as pyranols, the composition of which is largely chlorinated diphenyl. On the Continent also there are the clophens, which, too, are largely composed of chlorinated diphenyls. The degree of inflammability of pure chlorinated diphenyl, more familiarly known in this country as Aroclor, depends on the degree of chlorination. For instance, a compound 48 % chlorinated has a flash-point of 196° C. but is self-extinguishing. A compound 54 % chlorinated has no flash-point and, in addition to being itself non-inflammable, as is shown later in this paper, acts in the manner of a fire-extinguishing medium. The 54 % chlorinated compound Aroclor, which is largely pentachlor diphenyl, has two great drawbacks, however. The first is its price in this country, which is approximately 6 times that of ordinary transformer oil. Its use is thus precluded in electrical apparatus unless buyers of gear are prepared to overlook cost in the interest of safety of stations from fire risk, and it may well be that in face of the several serious electrical fires which have occurred during the last few years, the use of chlorinated diphenyls in some form or another may become, if not standard practice, at least a standard type of product of the leading manufacturers of electrical gear.

The second serious drawback is the shape of the viscosity/temperature curve. At 20° C. the 54 % chlorinated diphenyl is a pale yellow, rather thick, oil; at 60° C. it is practically as fluid as transformer oil; at + 5° C. however, it is practically solid. This compound is thus quite unsuitable for use in transformers unless thinned by the admixture of such other chlorinated synthetics as trichlorbenzene. This paper is confined, however, to pure chlorinated diphenyl compounds, so that the only apparent use of the 54 % chlorinated compound is as a non-inflammable filling medium for the busbar and current-transformer chambers of switchgear. The following interesting experiment has been carried out to determine the extent to which 54 % chlorinated Aroclor is non-inflammable. This experiment is illustrated by the two photographs shown in Figs. 3 and 4 (see Plate facing page 320), the first of which shows an open welded tank containing switch oil which was fired by heating from below with a fierce conflagration as depicted, actually obtained by burning wood wool. This steel tank is marked (1) in the photograph. Beside this steel tank containing the blazing oil is a small steel drum, marked (2), which contained 54 % chlorinated Aroclor, this drum having an open bung at the top. It will be seen that whereas the oil is burning freely, the Aroclor is not burning at all.

Table 3

SOME PROPERTIES OF 48 % AROCLOR

Specific gravity at 20° C.		1·456
Coefficient of expansion between 20° C. and 65° C.		0·000702
Acidity, as supplied ..		0·01 milligramme KOH
Sludge value, taken as for transformer oil B.S.S. 148—1933		Nil
Acidity after sludge ..		0·05 milligramme KOH
Thermal conductivity at	30° C.	0·0613 B.Th.U./hr./sq. ft./deg. F./ft.
	60° C.	0·0698
	100° C.	0·0800
Specific heat at	30° C.	0·290
	60° C.	0·339
	100° C.	0·405
Action on metals, insulating materials, etc.		Tests carried on over a period of a year at 100° C. have shown that this Aroclor has no deleterious action on copper, brass, aluminium, iron, and such insulating materials as paper, empire cloth, and cotton tape.

Fig. 4 shows that when the Aroclor in the small drum had become heated so as to have become quite fluid (approximately 150° C.), it was removed, and by means of a portable pump, was sprayed on to the burning oil. This photograph shows the lance and jet of the spraying apparatus, and also shows that the Aroclor has extinguished the oil fire, the flame and fumes from the burning oil being replaced by the dense white cloud of heavy fumes from the Aroclor.

This experiment demonstrated not only the non-inflammability of the Aroclor but that, in addition, it has the valuable property of acting as a fire extinguisher.

For use as a non-inflammable filling medium for transformers in place of transformer oil, the maximum chlorination compatible with suitable viscosity is 48 %. Here again, the shape of the viscosity/temperature curve is very steep compared with that for transformer oil, but the 48 % chlorinated Aroclor is just suitable. It is a water-white liquid at 20° C., and its viscosity at 35° C. is approximately the same as that of a Class A oil at 20° C. At 60° C., however, it is much thinner than Class A oil, but at 0° C., while A30 grade transformer oil is perfectly fluid, this Aroclor is quite viscous, its actual cold point being − 9° C. Thus at high ambient temperatures 48 % chlorinated Aroclor would possess an advantage over transformer oil as regards cooling by convection, but at 20° C. this advantage would be reversed, and at temperatures approaching zero Centigrade the Aroclor would be definitely dangerous. Some of the other properties of 48 % chlorinated Aroclor are given in Table 3.

It will be noted that the above grade of Aroclor has no sludge value as determined by the standard method laid down for oils, and, in addition, that there is practically no acidity developed during the sludge test. This in itself is a good indication of the stability of the material at the sludge temperature of 150° C.

It will be noted that the specific gravities of these chlorinated compounds are well in excess of unity, which imposes a condition upon the designer that no bare conductors should be brought through the surface of the medium in case water lying on the top should cause a breakdown along the surface of the medium. No suitable non-inflammable medium has so far been found for use in switch tanks or other places where arcs or sparking occur normally. The chlorinated compounds decompose under an arc and evolve free hydrochloric acid and probably free chlorine, and although it is possible for these to be absorbed above the level of the medium a risk is involved which few would be prepared to countenance.

An interesting property of Aroclor is the high dielectric constant, which is approximately 5 as compared with 2 for transformer oil. This fact is made use of in the manufacture of power-factor-correction condensers, where a 50 % increase in capacitance is obtained through the use of Aroclor instead of a mineral oil. Here again, however, the high price of Aroclor prevents its wider use in this field.

(3) CONDENSER OILS

Introduction

Although oils used in the manufacture of power-factor-correction condensers are in the main pure mineral hydrocarbon oils, service conditions are so severe that they cannot be used as delivered by the oil refiners, as can safely be done for transformers. Condenser oils have to be specially treated owing to the fact that they are not only used for filling condensers but also for vacuum-impregnating the paper dielectric. The following gives some idea of the special properties required of condenser oils and the special treatments attending their use.

Oil Impregnation of Condensers

The commonest type of power-factor-correction condenser is the paper-dielectric type, where the oil is used to add electric strength to the dielectric and, in addition, to fill the box containing the condenser spools, so as to exclude air and to aid cooling. It is of great importance that this type of condenser be hermetically sealed and that the vacuum impregnation be so efficient as to exclude all air voids in the dielectric. The stress in condensers is very high compared with other forms of electrical apparatus and, in the event of voids being formed, ionization occurs which causes decomposition of the oil, with subsequent breakdown. A further phenomenon in oil-filled condensers is that certain oils themselves are affected by severe electric stress with the evolution of gas, mainly hydrogen. This occurs mostly at the edge of the foil electrodes of the condenser where the stress is highest. Such oils must therefore be avoided. There appears to be a definite relationship between the amount of saturation of an oil and its tendency to generate or absorb gas; but this phase of the subject is as yet not fully understood. The estimation of the amount of saturation of condenser oil is usually made by iodine values. The apparatus shown has been used to study the absorption of gas by oils under electric stress. The body is constructed of soft glass, as shown in Fig. 5. A small piece of platinum wire is fused into the base of the chamber containing the oil, and the central electrode, which may be of nickel or tinned copper, rests on this; the collar at the top of the tube keeps it central. The outer electrode consists of a thin lead sheet which is wrapped round the outside of the glass tube and is simply wired into position. The electrode part of the apparatus is immersed in a beaker of oil for the test, and a potential of approximately 7 000 volts is applied. The oil under test is first saturated with hydrogen and then sucked into the tube via the manometer. When full, hydrogen is admitted through the three-way cock so as to enclose a suitable volume in the apparatus, and the amount of gas absorbed or propagated can be read off on the manometer, after suitable correction for the difference in the levels. Tests have shown that, under stress, oils either absorb or evolve hydrogen, and it is this property which is related to iodine value. It has been found that those oils having an iodine value of less than 6·5 give off hydrogen under stress; those with an iodine value exceeding 6·5 absorb hydrogen under stress.

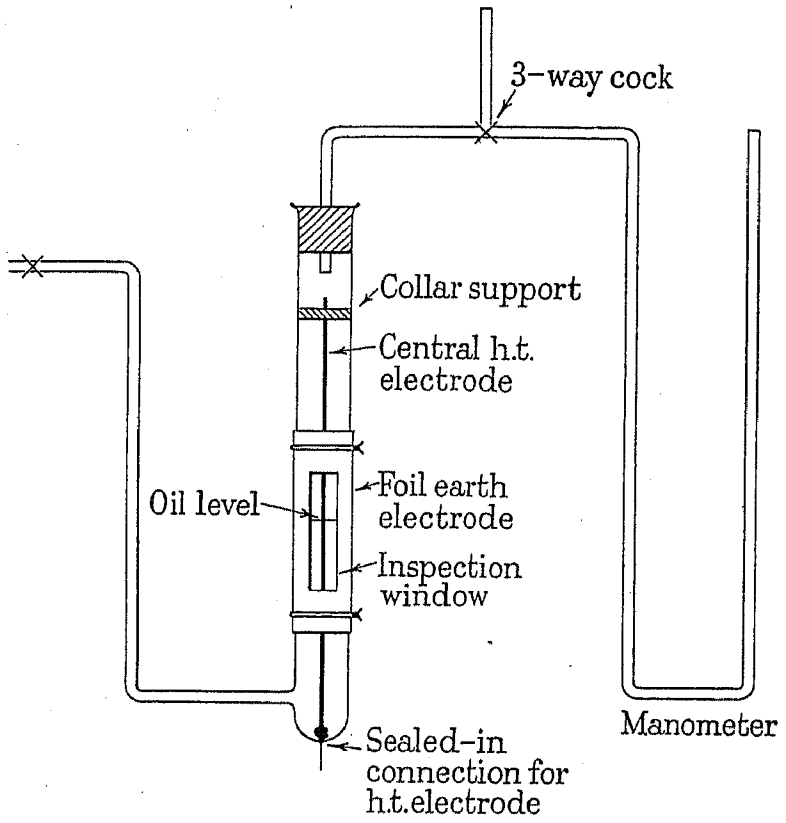

Fig. 5

The importance of this in relation to condensers will be appreciated; if through inefficient vacuum treatment the condenser has air voids trapped in the layers of paper or foil, these voids may be increased through the evolution of hydrogen, depending upon the iodine value of the oil. It is in the boundaries of these voids, if they are large enough, that the phenomenon of "cheesing" occurs. "Cheesing" is the formation of a wax-like solid well known in cable manufacture as being produced at voids under stress in oil-filled cables.

In other words, an oil having a higher iodine value than 6·5 will tend to counteract the effects of slightly imperfect vacuum impregnation, whereas the use of an oil of iodine value of less than 6·5 will cause the effects of imperfect impregnation to be gradually increased, with unavoidable subsequent failure. Wherever the condenser has been perfectly impregnated the gas-absorbing or gas-propagating property of the oil will not matter, as it is only where voids exist that the correct conditions for evolution of gas under stress obtain.

An oil of higher iodine value than 6·5, however, is relatively unsaturated and, therefore, more liable to oxidation than a highly refined oil of iodine value of, say, 2. This type of oil is also more easily contaminated, and precautions must be taken during its use to ensure that it does not deteriorate through oxidation in the impregnating process.

Precautions to be taken with High-Iodine-Value Oil

As delivered from the oil manufacturers, the power factor of new condenser oil is approximately 0·001 taken at a temperature of 70° C., which temperature is usually accepted as being the maximum permissible for operating condensers in service. It is found that after such oil is passed through two or three impregnating cycles, the power factor has increased owing to the oxidation of the oil. This means that the oil must either be scrapped or re-conditioned in some way so as to restore the power factor to its original value. It has been found efficacious to treat such oil with activated fuller's earth, by which treatment the products of oxidation in the oil are removed, and the oil is clarified and again restored to a usable power-factor value. It has been found sufficient to mix with the oil approximately $2\frac{1}{2}$ % of fuller's earth, agitate for an hour and then pass the oil through a streamline filter. The oil can be re-conditioned in this way many times and, as it is only the excess oil from the impregnating process which requires treatment, it is rarely found necessary to scrap any oil after use.

Precautions to be taken with Low-Iodine-Value Oil

As this type of oil is relatively highly refined, it is much more resistant to oxidizing influences than high-iodine-value oil and is found to deteriorate relatively slowly during use, so that the fuller's earth re-treatment method above described is rarely necessary. Using this oil, however, it is more necessary to attain high vacuum during the impregnating process so as to ensure absolute absence of voids in the condenser spool after treatment.

Where condensers are used with a free oil level, the choice of the most suitable oil becomes very difficult as, on the one hand, if a highly refined oil is used there is more chance of gas evolution, owing to the physical absorption of air by the oil and the subsequent danger of air voids finding their way into the dielectric. On the other hand, if a less highly refined oil is used, there is more danger of oxidation. The majority of power-factor installations in this country, however, provide hermetically-sealed condensers.

ACKNOWLEDGMENTS

The author wishes to express his thanks to the General Electrical Co., Ltd., for permission to write this paper; also to Messrs. W. B. Dick and Co. and Messrs. Monsanto Chemical Co. for data supplied for inclusion.

WRITTEN CONTRIBUTIONS TO THE GENERAL DISCUSSION ON THE ABOVE PAPER

Mr. B. Calvert: The positive tendency of a Class A oil to form acids, and their detrimental effect on the transformer, have now been recognized for several years, and it would be a step forward if B.S.S. 148 included tests and tolerances dealing with this property of insulating oils. The B.S.I. sludge test appears to be suitable for this purpose, and, in fact, I made the same suggestion in a paper read before one of the Students' Sections some weeks ago. The idea was not, however, elaborated as in the present paper.

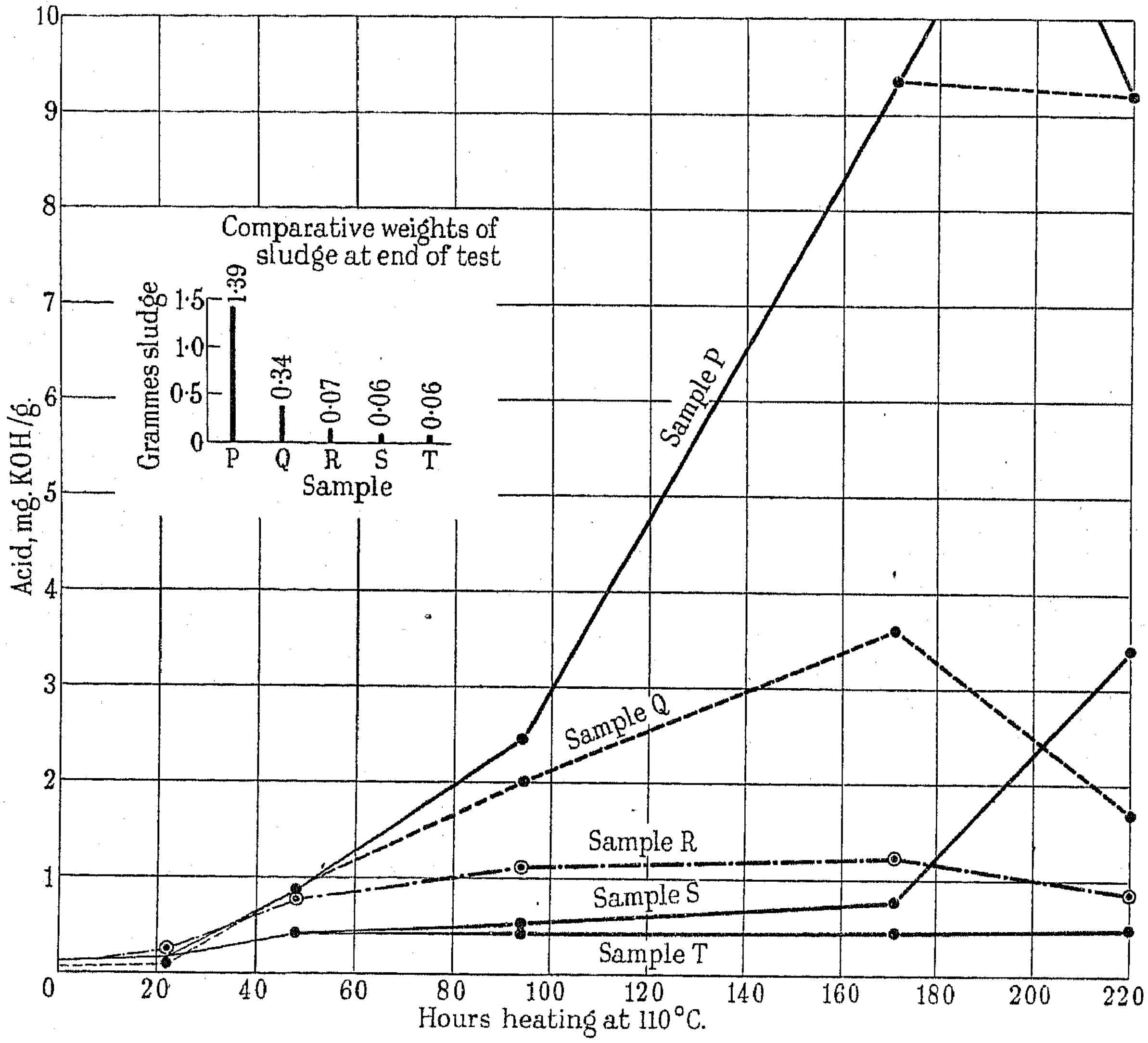

Fig. A.—Acid formation in various Class B transformer oils.

Acids formed by oxidation of the oil may be divided into relatively strong acids, soluble in water, and weaker acids, insoluble in water. It is suggested therefore that any test and specification which may be formulated should include a measurement of the tendency to develop water-soluble acids because of their greater potency.

Under differing conditions and with oils produced from crude materials obtained from various countries, different ratios of water-soluble to total acidity may also be found. But the problem is not wholly solved by ensuring that new oil shall be satisfactory as regards acid formation; there still remains the question of dealing with transformers and other apparatus now in service and filled with Class A oil.

Satisfactory results have been obtained, in cases where high acid values have been found in transformers, by changing the Class A oil for Class B after draining and washing the transformer with clean oil. The graph (Fig. A) of a case under observation shows that there has been no increase in acidity since the oil was changed 2 years ago, and the residual acid after cleaning has had no catalytic action on the formation of acid in the Class B

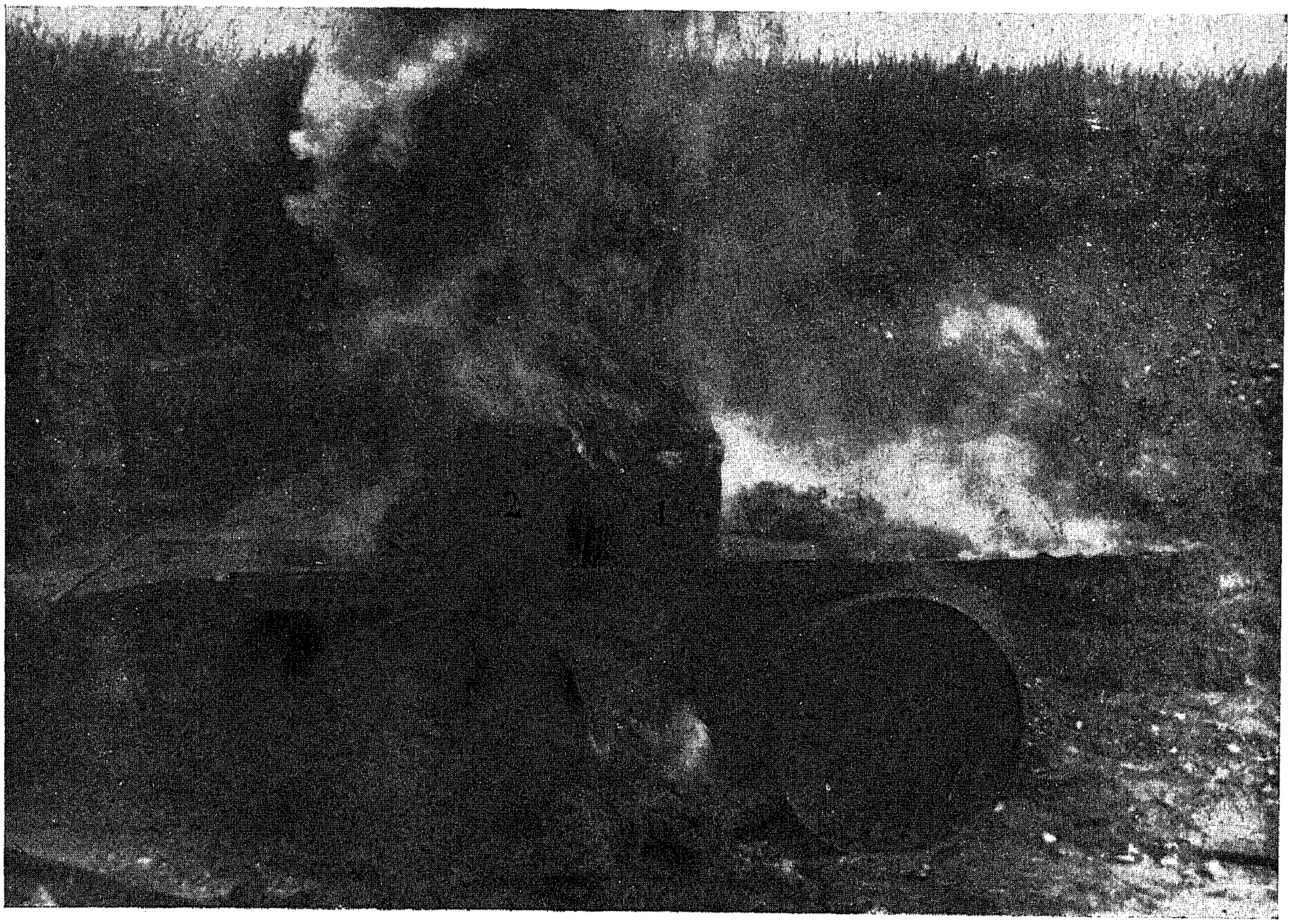

Fig. 3

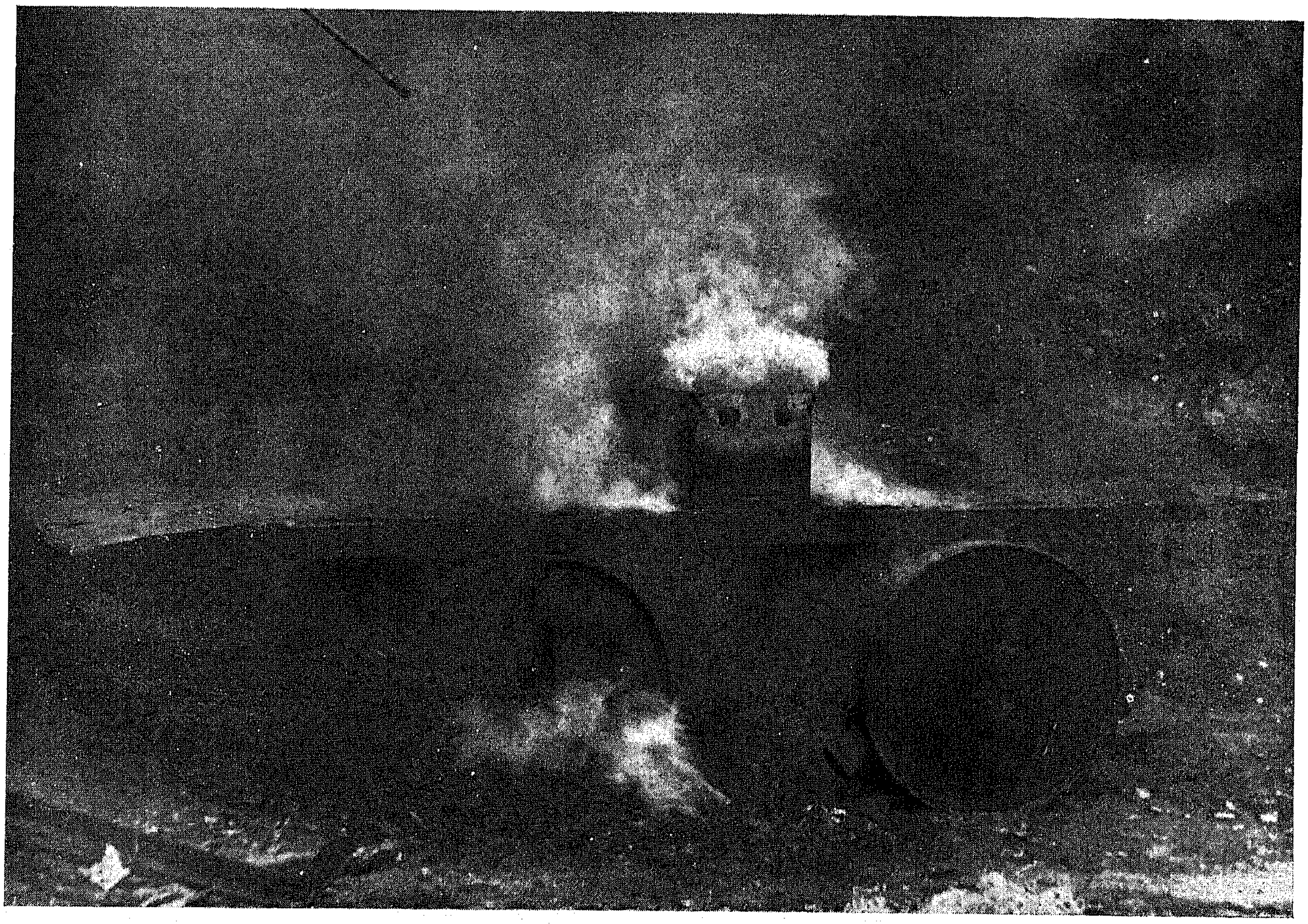

Fig. 4

oil. To render the Class A oil from the transformer fit for further use the acid has to be removed, and it would be interesting to know the author's experience in the treatment of oils for the removal of acid.

Transformers fitted with breathers are not so immune from corrosion as the author's remarks would suggest. In a transformer fitted with conservator and breather, corrosion takes place above oil-level inside the conservator. The products of corrosion can be sufficient to block the pipe between the transformer tank and the conservator. Explosion vents are similarly attacked should the bottom diaphragm be omitted or punctured. Instances have been noted in which top diaphragms made of metal have been perforated by corrosion, the oil thereby being exposed to the atmosphere.

Mr. A. D. Constable: The author discusses a practice in the use of high-powered electrical apparatus which has come to be regarded as normal and necessary, but which is nevertheless a serious evil, i.e. the incorporation of large volumes of inflammable material of high calorific value. It is bad enough with transformers, and worse with switchgear, in which a powerful arc may be formed in the oil. Besides some transformer fires there have been many oil-switch fires of greater or less severity, and but for the fact that large switches are infrequently operated on load the tale of disaster would be much worse. It is a case in which the very limited choice of materials for filling has led to the acceptance of risks which put the designs in the category of bad engineering. This may seem an exaggerated statement, but one cannot escape the conviction of its truth.

In dealing with switchgear the author could well have included, without going beyond the scope of the paper, water as a fluid filling-medium. The water-chamber switch may prove to be of some importance in the near future, and some reference to its present state of development would be of much interest. This type of switch and the air-blast switch are promising alternatives to the oil-filled type so largely used. Both avoid the risk of oil fires.

For transformer filling, the author evidently has with good reason a leaning towards the non-inflammable chlorinated diphenyls, but he refers to the objections of high cost and large viscosity range. The cost may fall appreciably with increase of production, and the use of large volumes is also not essential. Skilful design, in producing a high ratio of cooling surface to volume with rapid circulation, would limit the quantity of fluid required. The low viscosity of these compounds at ordinary working temperatures facilitates rapid circulation and permits the use of small passages. The defect of the high viscosity at low temperatures can be avoided by not requiring the material to do its work at such temperatures. By fitting heating coils in the fluid, thermostatically controlled if necessary, fed at low voltage by a small auxiliary transformer, the main transformer could be warmed up before being put on load, just as a turbo-generator has to be. It could also always be kept warm, ready for immediate use if necessary, and it is conducive to longevity if large electrical plant is not allowed to suffer large changes of temperature which enforce relative movement of conductors and insulators and of the windings and cores.

It would only be necessary to heat the fluid up to the point at which its viscosity becomes low enough for safety, and it would seem practicable to use the external cooling tubes, where fitted, as the conductors carrying the heating current.

It is true that there would be some further increase in initial and running costs if such a device were adopted, but the total increase might be well worth while as an insurance against fire risk, pending the discovery of a better medium than either chlorinated diphenyl or oil.

Large quantities of oil must of course be used for many years to come, for the purposes now under discussion, but the author advances figures which seem to show clearly that the present British Standard is not the best that could be devised to meet these requirements. If these figures are substantiated, the matter should not be allowed to rest where it is.

Mr. P. R. Coursey: I am particularly interested to note that the author criticizes the existing B.S.S. 148—1933 relating to Insulating Oils for Electrical Apparatus. I heartily support this criticism. In the first place the title of that Specification is so broad that it was obviously intended to cover all insulating oils other than those used in cables. The requirements laid down in the Specification, however, do not lead to the production of oils which are necessarily suitable for all electrical uses. It might have been better had the Specification been limited to insulating oils for electrical transformers, as then, doubtless, oil refiners would have been more ready to appreciate the fact that many electrical requirements call for oils differing materially from the requirements of this Specification.

To base the main classification of the oils, as in this Specification, upon their sludge values was, in my opinion, erroneous. It might have been effective if the scope of the Specification had been more limited, as suggested above. While the method specified is doubtless a practical test of a physical property of the oil, it frequently bears so little relationship to the conditions of use that the property so determined is of little real value in indicating the suitability of the oil when worked under those conditions of use.

Working to this Specification has undoubtedly led to a general over-refining of oils by many oil refiners. It is possible, however, that the author of the paper may not entirely agree with the implication of this statement, viz. that over-refined oils give poor electrical performance, since with the exception of one remark in the first section of the paper he appears to favour highly refined oils. The condemnation of highly refined oils may perhaps be too general for certain applications, as there is every probability that the properties of the finished oil depend not only upon the degree of refining but upon the method used in the refining processes and upon the nature of the crude material used.

It should not be overlooked that even in the best and most carefully manufactured apparatus it is impossible to avoid some traces of gas or moisture in the insulation that is impregnated or immersed in the insulating oil. Such traces will doubtless encourage oxidation of the oil, either directly or through some species of catalytic action, which, once initiated, will continue by the action of the electrical stress applied to the oil during its service use in the electrical apparatus.

On page 317 the author makes some suggestions for modifying B.S.S. 148. So far as the suggestion concerning the sludge test is concerned, I feel that this will only be valuable if the application of the Specification is confined merely to transformer (and reactor) insulation. It seems to be doubtful whether the proposed modification would be any more helpful when judging the quality of an oil where its application is as a dielectric rather than as a cooling medium.

Prolonged ageing tests under conditions approximating to the natural service conditions of the oil seem at present the only reliable method of selecting one oil from another. The need is therefore great for a proper accelerated test applicable to such uses. With this in view I would suggest that any modification of the B.S. Specification for these oils should involve a classification dependent firstly upon whether the oil is mainly used as a cooling medium or whether it is used mainly as a dielectric, when it will be subject to high electrical stresses. In the first case the thermal properties of the oil are important, that is to say its stability at elevated temperatures. In the latter the stability of the material under high electrical stress is a far more important property.

The A.S.E.A. sludge test has been claimed by some to be a more reliable test for many applications of insulating oils, but I do not feel that this one, any more than the Michie test, has been adequately proved as regards its reliability in judging one oil as compared with another for the two classes of applications indicated above.

The author states on page 313 that " the oxidation products of an oil at 150° C. are far different from those taken at 90° C." I would go further and say that the oxidation products, and the factors controlling the formation of such products, may again be quite different at 30° C. from what they are at 90° C. For some uses of insulating oil 90° C. represents a very high temperature, and the stability of the oil at much lower temperatures accompanied by electrical stresses is a vital factor. This again calls for consideration in any modification to the B.S. Specification, and emphasizes that any such revision should take count of the class of operating conditions—that is to say if and when revised the B.S. Specification is still to cover broadly " Insulating Oils for Electrical Apparatus."

In Section (3) the author refers to oils for condensers, apparently only for producing an impregnated-paper dielectric. There are other equally important uses in condensers wherein the oil either is the dielectric itself or is used with impervious dielectrics (for example, mica). It might be said that in the latter case the function of the oil can only be one of cooling, but I personally would rather include this with the dielectric application—as a classification grouping, as suggested above—since the electric stress that the oil will receive is usually much greater than in the case of most other cooling uses, and instability of the oil due to such conditions is by no means unknown.

On page 317 reference is made to the evolution of gas or vapour from liquid chlorinated compounds. It is equally possible to have vapour evolution from solid compounds of the same category when they are warmed up, which may be harmful—either from its corrosive character or from its toxic action.

I should like to ask the author whether the acidity figure of 0·05 mg. of KOH per gramme of oil referred to on page 313 for a new oil is regarded as a reasonable figure for all purposes. For the dielectric uses, I suggest that this is not the case, and that for uses of this character this figure is nearer a rejection limit for a decomposed oil than an acceptance figure for new material.

The " dielectric " uses of these oils certainly seems to confirm the statement made at the end of page 315, since oils otherwise similar but derived from different crudes have given markedly different electrical performances. It is to be hoped that the revision of B.S.S. No. 148 will not be much longer delayed, and that the various proposals put forward by the author and others will be given adequate consideration.

Mr. E. A. Evans: As the British Pharmacopoeia sets the standard for medicinal paraffin, it might be a little dangerous for an electrical engineer to state, as the author does, that transformer oils even of the " B " quality could be safely used medicinally.

When B.S.S. 148 was issued in 1923, the prevailing opinion was that it contained the accepted opinions in this country. The revised edition of 1933 was issued after very careful consideration by all interested. It is not true to say that it was published " without very much attention being paid to its other properties." All other known properties were considered, even the production of free acid, and the views of our counterparts on the Continent were noted. Since then changes have occurred which merit a re-consideration of the subject as a whole. On my return from the meeting of the International Electrotechnical Commission at The Hague in 1935 I drew serious attention in appropriate publications to the acidity problem and hazarded a guess that before very long the " A " grade in its present form would disappear from the English market. My remarks caused a little flutter at the time, but now they are materializing.

Acid-producing oils are not welcome to-day, but is it quite true to say that the problem has been satisfactorily solved? Surely it takes years to prove a transformer oil. Do not therefore judge the rest by a sample. Let the petroleum industry express its opinion on the reproducibility and availability of any suggested oil. Unfortunately, under war conditions it is not easy to obtain that opinion. Perhaps the author will be compelled to use, while the war lasts, an oil of different origin from that which he has grown accustomed to use. When peace is restored we shall all be very eager to return to the subject.

Mr. T. A. Evans: I particularly welcome the section on transformer oil, as, generally speaking, the acid-development feature has not been sufficiently understood by the user. We are doing investigational work on acid formation, using the standard Michie apparatus but at a temperature of 110° C. This temperature was chosen as being sufficiently high for an accelerated test while avoiding the complications of the standard temperature of 150° C. The first part of the investigation, however, was over a period of only 220 hours, and very interesting results were obtained. Fig. B shows curves of the acid formation of samples of Class B oil from different suppliers. It will be noticed that in three cases the acid value has reached a peak and then decreased, while sample S suggests that it is about to form a peak. This in part confirms the opinion held by Continental workers that both acid formation and sludge formation occur in cycles, a decrease in acid value coinciding with an increase in sludge—a case of repetition of a cycle (*a*), (*b*), (*c*), where (*a*) is oxidation of part of the oil to acids, (*b*) is oxidation and polymerization of the acids to form sludge, and (*c*) is the chemical breakdown by heat of the sludge to form acids. If this peak value is reached in a short time, as suggested by the curve, it would possibly not show up on tests where samples were tested only at long intervals, although we have not yet correlated rate of ageing of oil at 110° C. with rate of ageing at 80–90° C.

Referring to the paragraph in the paper relating to method of refining, the statement appears "... whereas by removing all aliphatic constituents an oil of low acidity formation is produced," I presume that the word "unsaturated," qualifying "aliphatic," has been omitted.*

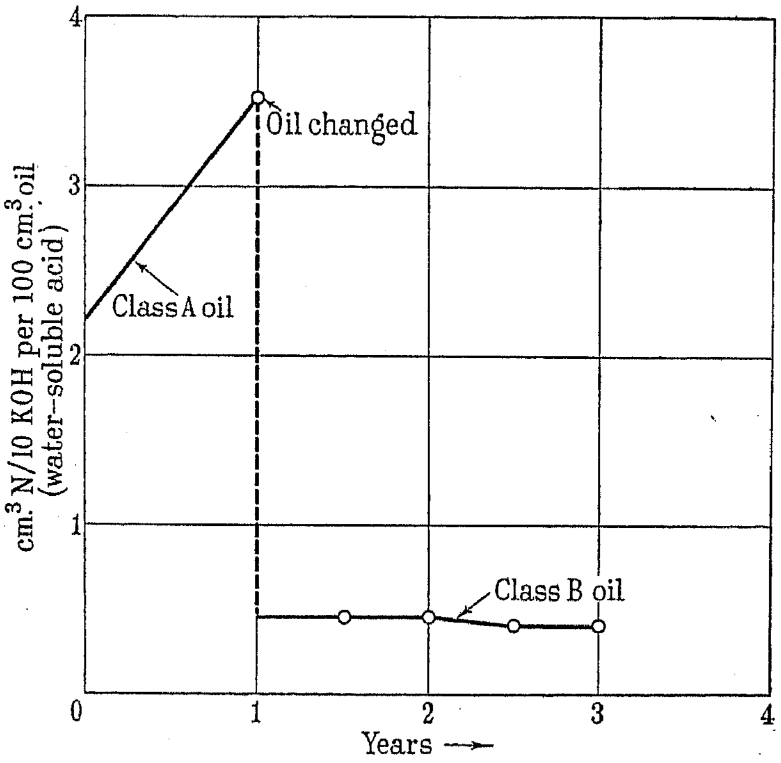

Fig. B.—Formation of acid in transformer oil (400-kVA transformer).

Finally, with regard to the case of chlorinated hydrocarbon liquids it may be as well to note that they are very active solvents, and that no varnish (including bakelite) must be used on any part of the transformer inside the tank. The insulation should be either untreated cellulose or cellulose acetate.

Mr. C. J. O. Garrard: It is probable that most of the serious switchgear breakdowns during the last few years which have been due to fire would not have occurred had the busbar structure and instrument transformer chambers contained some such non-inflammable filling medium as that mentioned by the author. It is important to notice in this connection that oil contained in the circuit-breakers themselves has played a very small part in these fires. In one case in my experience the oil in the circuit-breaker tanks was practically untouched after a fire that had entirely destroyed a large metal-clad board and the building in which it was contained. The reason is, of course, that the circuit-breaker tank must be of very strong construction in order to ensure reliability of operation under fault conditions. It is, however, impracticable to adopt a similar construction for the busbars and transformer chambers. If the oil or compound in these chambers is replaced by a non-inflammable material, the total quantity may be reduced to a very considerable extent, particularly if the busbars themselves consist of condenser bushings so that only the joint boxes between adjacent sections need filling. If Aroclor is used, as the author remarks, it has itself a considerable fire-extinguishing effect, so that the result is a large reduction of the total fire risk.

The cost of the filling is, of course, a noticeable proportion of the cost of the gear, although the proportion falls off as the size of gear increases. It is to some extent offset by the saving in fire-fighting equipment, which is scarcely necessary if non-inflammable filling be used.

Dr. J. F. Gillies: The author deals with the relative behaviour of Class A and Class B oils under normal operating conditions. Much work has been carried out in the past on similar problems, while the physico-chemical nature of the oxidation process has also been investigated, notably by Ornstein and his collaborators. The value of this section of the paper would have been enhanced greatly by a bibliography and by some reference to such earlier work.

It has been realized for some time past that the British Standard method of testing transformer oils does not necessarily give a fair basis for comparison between different oils, and the author suggests that the temperature of the sludge test should be reduced and that a determination of developed acidity should be made after sludging. The objection has been raised* that the determination of developed acidity by titration with sodium hydroxide is of doubtful value as an indication of the deterioration of the oil, because (*a*) all the deterioration products are not necessarily acid in character, (*b*) some of the acid products, particularly in over-refined oils, are volatile; and (*c*) saponification of certain constituents under the action of the sodium hydroxide may make the end-point of the titration uncertain. It may be desirable, therefore, to avoid such difficulties by determining the actual deteriorating effect of the oil on cotton fibres, rather than to attempt an acid determination which may be difficult to standardize and which does not differentiate between the types of acid produced in different oils. The decrease in tensile strength of cotton yarn, as in the Swiss test,† measures the actual damage which may occur due to acid formation in the oil during service.

It is desirable that the sludge test should be carried out at a temperature as close to the normal operating temperature as possible, but a higher test temperature may be used provided that the increase of temperature merely accelerates the process without altering materially the nature of the products. If, however, the temperature of the sludge test is reduced, it becomes necessary to extend the period of heating in order to obtain the same quantity of sludge. There appears to be an induction period before an appreciable quantity of sludge is produced, after which sludge formation proceeds much more rapidly, and it is important that the period of oxidation should be sufficiently long compared with this induction period for all the types of oil which may be tested. It has been shown that the development of acidity precedes both the deterioration of the insulating properties of the oil and the deposition of sludge.* Hence the acid test after sludging, in whatever form it is adopted, may detect a tendency to decomposition, even though sludge has not been deposited to a marked extent during the period of the test.

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* The correction has been made for the *Journal.*

* E. LECLERC: *Société Belge des Électriciens*, 1937, **53**, pp. 390 and 467.

† H. STAEGER: *Brown-Boveri Review*, 1922, **9**, p. 159.

Tests by Muller† throw some light on the nature of the oxidation process. They show that the catalytic action of copper is slight in the case of over-refined oils, and this may explain the figures which the author obtains for the acid development with varnished and with unvarnished coils. The difference in the two cases for Class A oils [see Table 1(A)], which may be regarded as over-refined oils, is comparable with the differences in acid development between different samples of Class A oils heated by varnished coils. On the other hand, the use of unvarnished coils in the case of Class B oils causes a marked increase in acid development.

The above-mentioned worker observed also that the amount of oxygen absorbed by transformer oils during oxidation varied widely with different oils under the same conditions. The oxygen absorption of an oil which has been refined to the optimum extent appears to be a minimum, while over-refining results in a rapid increase in the oxygen absorption, suggesting that the oxygen absorption might usefully form part of a specification for transformer oil.

Finally, I should be glad if the author could give any detailed information regarding the effect of the method of refining and of the type of crude oil on the properties of the oil. In this connection, the results given in Table 2 would have been more informative if the observations had been made concurrently with the acid determinations given in Table 1, and if they could have been related to the fundamental chemical constitution of the various samples.

Mr. A. L. Morris: The author mentions corrosion of the tank covers of transformers due to the action of volatile acid products in the transformer oil. Trouble of this nature appears to be more pronounced when the transformer is air-tight and unable to breathe properly. The provision of an air escape vent seems to be warranted in such cases. I should like to ask whether the oil in hermetically sealed transformers of the expanding diaphragm type would be likely to attain a high acid content owing to the impossibility of escape into the atmosphere of these volatile acid products.

Mr. D. V. Onslow: Section (1) of the paper does not cover any new ground or offer any new suggestions. The author's criticism of the B.S. sludge test has been anticipated by the Electrical Research Association, who have realized that as a result of the march of time the original Michie sludge test requires modification and supplementing. The Association, in co-operation with all the user interests and the principal oil suppliers, have for a number of years past been carrying out investigations on transformer oil with a view to recommending oils which would have less tendency to acid formation than the present grades, without sacrificing sludge value. Many hundreds of tests have been carried out on oils from various sources and with various degrees of refinement in order to determine the most suitable limits of sludge and acidity for inclusion in a revised specification, and to develop the best method of test for acidity after sludging.

The question of reducing the temperature in the sludge test has been given special attention over a number of years, and numerous tests have been made at temperatures of 100°, 110°, 120°, 130° and 150° C., for periods of 45, 48, 72, 96, 200 and 1 000 hours, and also with various rates of air flow. The volatile and non-volatile acidities, including determinations of CO_2 and moisture, have also been studied. The investigations have shown that two oils may sometimes have a different order of sludging when tested at 120° C. for 72 or 96 hours from that when tested at 150° C. for 45 hours, and that sometimes an oil may give a better or worse result at the lower temperature than at the higher temperature. With certain oils the difference in the tendency to sludge, which is shown up readily in the high-temperature test, does not develop in the low-temperature test, except as a result of a sludging period which would be far too long for general routine practice; at the same time the low acid-forming tendency of a good oil is still shown by the high-temperature test.

As an indication of the thoroughness with which the research has been carried out, it may be mentioned that the investigations have always been made by at least three investigators in order to see how concordant the results would be. The temperature of test was kept within ± 0·5 deg. C., and similar glass flasks were used by all investigators as it was found that the type of glass sometimes affected results.

Our investigators have tentatively agreed to keep the temperature at 150° C. for acceptance tests and to recommend the inclusion of an acidity test after sludging, with a limit for acid value of 2·5 mg. KOH/g., which would eliminate high-acidity oils. The limit of acidity for the oil as delivered is proposed to be 0·02 mg. KOH/g., instead of the present figure of 0·2. For research work a lower temperature would be used in addition to 150° C. It was felt that though 150° C. might be rather far removed from operating temperatures, all tests were equally arbitrary and others did not give better results, and the use of the higher temperature would enable results to be obtained more quickly.

In proposing the above figure of 2·5 mg. KOH/g. for the acid value, it was appreciated that while a Class B type of oil existed which would comply with this specification, there did not appear to exist at present a Class A oil which would comply. Research, however, is proceeding with a view to the production of such an oil.

No cases of trouble due to Class A oils have been brought to our notice where conservator tanks or breathers have been used, and two large makers of transformers of this type have stated that they have had no trouble with either Class A or Class B oils. Trouble has been experienced with some transformers without conservator tanks or breathers using Class A oil. In these cases it is possible that there was an abnormal access of moisture to the oil, and that had the oil received more frequent examination and attention the extent of the trouble might have been much reduced. Amongst the products of oxidation of transformer oils are CO_2, water-soluble volatile acids, and water. These, in combination, can attack and corrode iron and other metals, and in some instances corrosion of the lids of transformers has occurred owing to the condensation thereon of the water in which is dissolved the CO_2 and some of the volatile acidity. The provision of breathers not only prevents the ingress of damp air to the oil, but helps to absorb any moisture formed from the oil *per se*.

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* J. F. Gillies and J. V. Black: *World Power*, 1936, **26**, p. 163.
† *Comptes Rendus*, 1935, **200**, p. 1769.

The type of insulating varnish used and insufficient baking may cause excessive oxidation of the oil; some insulating varnishes are not sufficiently resistant to moisture in warm oil. It would appear from the results given in Table 2 showing the condition of the oils after six months' test that Class B oil (Ref. A) shows much more deterioration from the effect of the varnish than it does from the action of bare copper.

The Association has tested every 6 months for a period of 10 years the oil from transformers at 3 large generating stations, the transformer ratings being 6 500 and 12 000, with conservator tanks and the oil Class A. During the first 5 or 6 years the acid value gradually rose to about 0·17 in two cases and 0·20 in the other. It has remained fairly steady for the next 5 years, being in the tenth year 0·19, 0·21, and 0·23.

The word "acidity" appears to frighten some people, and it might be better to call it "neutralization number," as in the U.S.A.

Mr. F. Meyer (*in reply*): I am gratified to note that the written response to my paper takes mainly the form of support of my criticism of B.S.S. 148, showing that the development of acidity in transformer oils is a live question in the industry.

Mr. Calvert and Mr. Evans in their communications have supplied information amplifying my remarks on the subject of acid formation and, altogether, there seems to be a general demand for this question of developed acidity to be taken care of in the modified B.S. Specification now in course of preparation.

Mr. Calvert raises the interesting point of the removal of acid from transformer oil which has been in service. In my experience, ordinary centrifugal and filter methods, which include washing with water, remove very little of this developed acidity. The only way in which it can be substantially removed is by means of an alkali wash. On the market there is apparatus which treats the oil with caustic soda, and I have found that after such treatment, followed by drying and treatment with fuller's earth to clarify the oil, the resultant treated oil appears to be as good as when originally refined. Indeed, it may well be that such treated oil may give better results than originally, having lost its initial active tendency to develop acidity.

Mr. Constable's remarks on the subject of switchgear design show how fortunate the industry has been as regards fires, when the extent of the risk in using oil is realized. I am well aware of the alternative designs which Mr. Constable mentions, and there is little doubt that the modern development of the air-blast circuit-breaker points the way to the real cure for the fire risk when using oil, viz. not to use it at all. The water switch has been thoroughly investigated in this country, but discarded owing to its limitations in suitability for really high voltages. The fact that the switchgear designers of this country have the oil fire-risk well in mind is also shown by the modern development of "oil poor" circuit-breakers, in which the amount of oil used is cut down to a minimum. Mr. Constable's suggestions as to how to overcome the low viscosity of the highly chlorinated diphenyls are very helpful and of value to transformer designers, who might find difficulty in dealing with this point.

Mr. Coursey's suggestion that insulating oils should be classified in accordance with their intended use, either as a cooling medium or as a dielectric, is very sound and, in my opinion, ought to form the basis of any new classification adopted by the British Standards Institution. In this case it would seem necessary to define an accelerated ageing test for oils intended primarily for use as dielectrics where the oil is subjected to an electric stress during the test. Some form of the Michie test could be retained for an ageing test for those oils intended primarily as cooling mediums, and a simple modification could, no doubt, be devised to subject the oil under test to electric stress in order to cover the dielectric type of oil. Regarding the acid-value figure quoted in my paper as 0·05 mgm. KOH, I should like to point out that it is quite common for a new oil to be of this order, but I agree that it could not be regarded as a satisfactory value for oil intended mainly as a dielectric.

I regret that Mr. Evans has apparently misunderstood my reference to liquid paraffin, as it was meant in a comparative sense only, with strict regard to the degree of refinement used in manufacture. There is little doubt that Mr. Evans's prophecy regarding the "death" of Class A oils is materializing; the advent of the war is, in any case, hastening its departure.

The experiments carried out by Mr. Evans are particularly interesting to me, as they deal with tests carried out at 110° C. His curves show particularly clearly the difference in performance between Class B oils from different manufacturers. This supports my contention that the composition and origin of the crudes from which the insulating oils are refined are of importance and worthy of study.

I am grateful to Mr. Garrard for his remarks in support, as representing the opinion of an engineer faced with the problem of oil fire-risks with large switchgear.

I have to thank Dr. Gillies for his interesting comments and additional information on the subject of acidity development. As I pointed out in the paper, my suggested method for the determination of acid value after sludging did not take account of all volatile acidity, but my proposed test has been found efficacious for the purpose even if it does not tell the complete story. The introduction of traps for all the volatile acidity would make the already rather cumbersome sludge apparatus much more so, which for general specification purposes is not desirable.

The Swiss test is much too long for a B.S. Specification and, in any case, standardization of cotton yarn would present difficulties, as would also the interpretation of results when obtained. One must not lose sight of the fact that, for specification purposes, the test should be as simple and short as possible.

The measurement of the oxygen absorption of an oil is a very interesting suggestion, and would be of value if it could be definitely correlated with the ageing properties of an oil. As shown in the "Condenser oil" section of the paper, the hydrogen absorption is related to the iodine value, but this latter has usually been considered to be an unreliable guide to the sludging properties of an oil.

I am afraid that I cannot give any reliable information on the subject of the methods of refining and the types of crude oil as related to the behaviour and properties of insulating oils; this, I feel, is more a matter for the petroleum technologist than for the electrical engineer.

Mr. Morris raises an interesting query appertaining to hermetically sealed transformers. In these conditions the amount of air available for oxidation of the oil would be very limited, so that, in my opinion, acidity would be unlikely to develop in large quantities.

Mr. Onslow's contribution is of interest for two reasons. First, because he makes use of unpublished information which I had in my possession but was not permitted to use. Secondly, because it is clear from this that my remarks about the Michie test have the support of the Electrical Research Association. In this connection, however, it is disconcerting to find that the investigators with whom Mr. Onslow is associated have decided to continue the unscientific practice of making concessions to convenience (in the matter of time and temperature) which can be shown on his own evidence to defeat the object he has in view.

The suggested limit for developed acidity after sludging of 2·5 mg. KOH is, in my opinion, not helpful, as many oils are now available conforming to this requirement. As I mentioned in the paper, Class B oils with as low a developed acidity as 1 mg. KOH have been produced on a small scale and, in the opinion of oil technologists, could be produced in the large quantities required by the electrical industry. I suggest, therefore, that the more useful limit of 1·5 mg. KOH should be adopted, giving a concession to oil suppliers on the one hand, and satisfying the requirements of the engineer on the other.

AN IMPROVED CELL FOR THE A.C. AND D.C. TESTING OF INSULATING OILS*

By L. N. BRAMLEY, Ph.D., M.Sc.(Eng.), Associate Member.†

(*Paper first received* 1*st November*, 1937, *and in revised form* 17*th October*, 1939.)

SUMMARY

The criteria of quality of an electrical insulating oil are stated, and the requirements for an ideal oil test-cell enumerated. The factors defining the cell dimensions are briefly discussed and an improved cell, designed to fulfil the above requirements, is described. A brief account is also given of experimental work which was carried out to determine the best length of test-gap for the cell.

The simple procedures necessary for setting up the cell for test, both whilst empty and when filled with oil for testing, are described.

INTRODUCTION

The difficulties associated with the electrical testing of insulating oils have been the subject of much research during the last ten years and, although considerable progress has been made in the subject, suitable apparatus for the production of accurate test data is not yet in general use.

Apart from breakdown strength, which is not dealt with in this paper, the electrical quality of an insulating oil is assessed from a knowledge of:—

(*a*) D.C. resistivity/temperature characteristic.

(*b*) Dielectric-loss-angle/temperature characteristic.

(*c*) The variation produced in the above characteristics by oxidation of the oil.

The chief object of the present paper is to describe a new oil test-cell designed to furnish accurate data on these.

REQUIREMENTS IN DESIGN

A close study of the problem of designing an oil test-cell shows that the cell should have the following properties:—

(1) The cell must have a negligible dielectric-loss angle, when empty, over a temperature range 20° C. to 80° C.

(2) Guarding and screening must be efficient, in order to avoid errors due to concentration of stress and to surface effects.

(3) The cell must have a uniform gap so that the oil under test is subjected to a uniform stress.

(4) The design must be such that the cell will be applicable to both a.c. and d.c. testing of oils.

(5) The cell should require less than 100 ml. of oil.

(6) It must be robust, and the operations of assembling, filling, emptying and cleaning must be simple and certain.

(7) It must be adapted for precise temperature control

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* This paper is taken from a thesis entitled "The Electrical Testing of Insulating Oils and Compounds" successfully submitted to the University of London for the degree of Ph.D. in the Faculty of Engineering in 1938.

The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† Royal Aircraft Establishment, Farnborough, formerly with Messrs. W. T. Henley's Telegraph Works Co., Ltd.

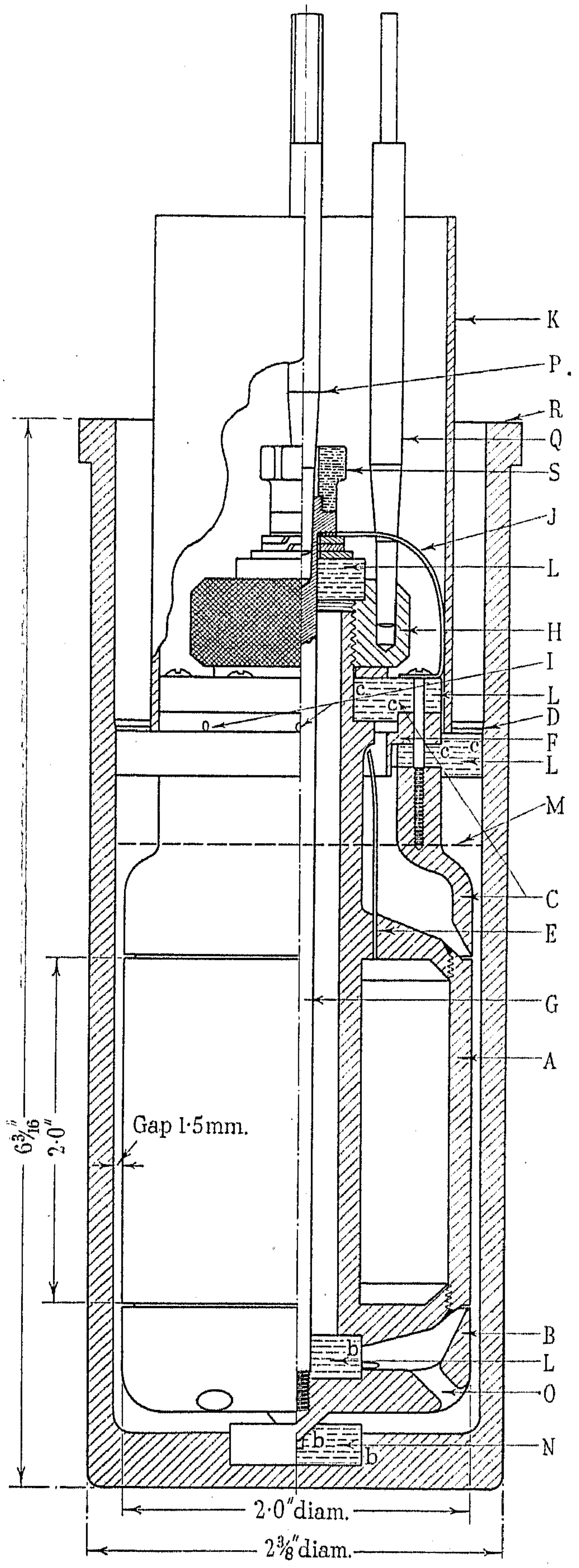

Fig. 1.—Cell for routine d.c. resistivity and dielectric loss-angle tests on oils and compounds.

A. Low-voltage electrode.
B. Lower guard.
b. Surfaces maintaining concentricity at lower end.
C. Upper guard assembly.
c. Surfaces maintaining concentricity at upper end.
D. 0·005 in. step.
E. Breather tube.
F. Guard ring with screen for lower insulation ring.
G. Central rod.
H. Main assembly nut.
I. Breather-holes.
J. Phosphor-bronze guard link.
K. Upper shield cylinder.
L. Mycalex rings.
M. Oil level.
N. Mycalex disc.
O. Oil holes.
P. Guard terminal.
Q. Low-voltage terminal.
R. Ground lip.
S. Tufnol cap.

and must attain an even temperature distribution over the test gap in a short time.

It is of interest to consider the first of these requirements in more detail.

In order to give a zero dielectric-loss angle when empty, the cell must be equipped with correctly designed guards and screens, which form a third electrode to the condenser. The arrangement is such that there can be no direct leakance between the high-voltage and low-voltage plates, since any insulation bridging them is, as it were, cut into two, and earthed guard plates are inserted in the resultant gaps.

DESCRIPTION OF THE CELL

The electrodes of the cell to be described consist of concentric cylinders as shown in Fig. 1. The actual size of the cell depends on a number of factors. The sensitivity of a Schering bridge increases with the capacitance of the cell, and the difficulties and errors associated with a.c. oil testing increase as the dimensions decrease. The cell must be of reasonable size for handling and heating requirements, but it must not be too large in order to avoid errors when being used with a d.c. direct-deflection testing set at elevated temperatures.

The length and diameter of the inner electrode are both 2 in. The overall height of the outer cylinder is not less than 6 in. in order to ensure that, with the cell almost completely immersed in an oil bath, the test portion is not less than 2 in. below the surface of the oil. This requirement is very necessary for the accurate measurement and control of temperature of the oil cell, but so far as is known, it has been largely neglected in previous designs.

Referring to Fig. 1, the main low-voltage electrode A and the lower and upper guards B and C respectively, are clearly shown. Concentricity is maintained by the locating surfaces at "b, b, b" and "c, c, c, c" for the guards, and the outer electrode is increased in internal diameter by 0·005 in. at D to facilitate entry of the inner assembly. The latter is of composite structure as shown and is equipped with a small breather tube E. The upper guard assembly, which locates the upper end of the inner electrodes in the outer shell, is removable in one piece, the procedure in dismantling being to unscrew the lower guard from the central rod G, withdraw the latter and unscrew the large knurled nut H when the complete upper-guard assembly may be removed. This is all the dismantling necessary for cleaning the cell after use.

The guards, connected by the rod G and the phosphor-bronze strip J are insulated from the low-voltage electrode by mycalex rings or discs, as shown, and direct leakance between high- and low-voltage electrodes is avoided by the presence of the guard rings B, F and C, respectively. A small screen attached to F ensures that the lower mycalex ring of the upper guard is not exposed to the high-voltage/low-voltage field, whilst an upper shield cylinder K is arranged to slip over the top mycalex ring for a similar purpose and in order to avoid errors due to direct fields between the upper parts of the low- and high-voltage electrodes, respectively. Solid taper pins, projecting above the outer electrode, form connecting points for miniature "crocodile" clips on the Schering bridge low-voltage leads, and a further screening superstructure, not shown in Fig. 1 but normally resting on the screen K, serves to screen the exposed ends of the leads.

Fig. 2 summarizes data obtained with the object of determining the best value for the gap between the inner and outer electrodes of the cell. The curves, obtained by means of a three-electrode flat-plate variable condenser of special design, show the variation of apparent d.c. resistivity of a cable insulating oil with test gap for a number of different temperatures.

The data show that the apparent d.c. resistivity increases comparatively rapidly with decrease of gap below 1·0 to 1·5 mm. The test gap of the cell under discussion is thus made 1·5 mm., this being the minimum value consistent with reasonable independence of apparent d.c. resistivity upon the test-gap length.

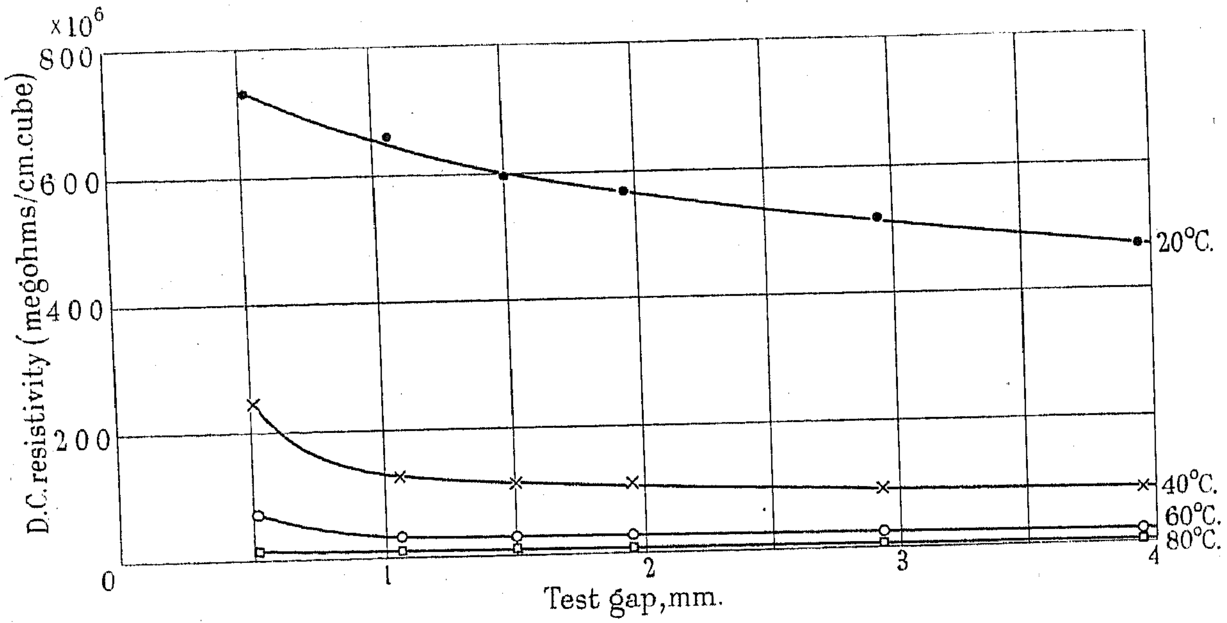

Fig. 2.—Variation of apparent d.c. resistivity with test gap at different temperatures for a cable-insulating oil.

CONSTRUCTION OF THE CELL

The cell can be made up in any normal workshop to the drawing shown in Fig. 1. It is best fabricated of high-grade brass, and finally chromium-plated in order to avoid oxidation troubles. Mycalex can be machined to fine limits by means of " Wymet "-tipped tools.

SETTING UP THE CELL FOR TEST (EMPTY)

The cell is taken apart and each of the components, except the upper guard unit, rinsed in clean acetone and dried with an electric drier. In cleaning the upper guard the mycalex is only wiped with a leather damped with acetone, as experience has shown that, with guards of this nature, errors may arise if the guards become totally immersed during cleaning. Apparently acetone becomes lodged between the metal-to-mycalex surfaces of the composite guard, with the result that, on assembly of the cell, the acetone evaporates slowly and the heavy vapour pours down into the test gap, causing erratic results.

After assembly of the cell it is lowered complete into the oil bath and lagging, screened leads and screening superstructure are placed in position. It is then ready for test.

SETTING UP THE CELL FOR OIL TESTING

To set up the cell for testing an oil it is cleaned as already described, assembled and heated to 80° C. in an oven. The inner electrode assembly is then removed and 62 ml. of the oil, also at 80° C., are poured carefully into the outer electrode. The inner assembly is then slowly lowered into place, with the cell held at a slight angle to the vertical for the first part of the operation. The holes in the lower guard, shown in Fig. 1, facilitate flooding with oil of the cavity above it, whilst holes in the metal ring between the mycalex rings of the upper guard allow air to escape at a later stage, with flooding of the upper cavity.

When cold the cell is lowered into the oil bath, connected up, screened and lagged as already described.

Acknowledgment

The author wishes to express his gratitude to Dr. P. Dunsheath, Chief Engineer of Messrs. W. T. Henley's Telegraph Works Co., Ltd., for valuable advice and for permission to publish this paper, and to Mr. W. C. Barry, Research Officer of the Henley Research Laboratories.

SUPERIMPOSED CONTROL APPLICATIONS, WITH SPECIAL REFERENCE TO TARIFFS AND LOAD-LEVELLING

By D. J. BOLTON, M.Sc.(Eng.), Member.*

[*Paper first received* 14*th October*, 1938, *and in revised form* 18*th January*, 1939; *read before the* TRANSMISSION SECTION 10*th May*, *and before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 6*th March*, 1939.]

SUMMARY

Last session a paper was read before this Section on "The Centralized Control of Public Lighting and Off-Peak Loads," by Mr. H. P. Barker.† Most of this paper, and a still greater part of the discussion, concerned technical factors and the details and operation of the various systems. The present paper takes the technical side for granted, and assumes the feasibility of some system of remote control capable of sending out several distinct signals and of operating the appropriate circuit relays. It concerns itself with the possible applications of such a system, and, moreover, confines itself to applications instigated by, and primarily for the benefit of, the undertakings rather than the users. It therefore deals with the uses of a control system in connection with tariff and peak-load problems rather than with such things as street-lamp switching.

In the past, supply development has largely lain in the fields where electricity is markedly superior to other agents, and where a public supply is more convenient than private generation. Now that these fields have been fairly fully exploited, the time has come to explore some of the less obvious markets. Two difficulties which lie in the way are both concerned with the high cost of peak supplies. One difficulty arises because our present tariffs are so empirical that it is impossible to make a close quotation; and a second difficulty is that some applications of electricity have so relatively low a yield that they can scarcely carry any peak charges. Both these difficulties are dealt with in the paper, and it is shown how superimposed control can be employed in connection either with paying for the peak or with avoiding it.

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BASIC PRINCIPLE OF ELECTRICITY SALE

The essence of an electricity sale, as of any other sale, is that it is a free transaction taking place between two (more or less) free and informed agents. It follows from this that both parties to the transaction must be satisfied that they are obtaining "value," i.e. that what they receive is worth more to them than what they give. These two aspects may be briefly enlarged upon.

The purchaser on his side will only consent to consume so long as each unit he buys adds to his pleasure and satisfaction as much as it takes from his pocket. In economic phraseology, the price of the last unit he buys cannot exceed the value of the marginal or added satisfaction obtained. But the only criterion of the monetary value of the satisfaction received is the price of similar pleasures or competing avenues of satisfaction. Electricity *per se* may be an "inestimable" boon, but these unique qualities are discounted the moment our householder becomes connected, and his subsequent load will be rigidly determined by hard economic facts. He will only consume up to the point when the last unit bought gives him more or better light, heat, and service, than he can buy for this money by other means.

The seller of electricity must in a similar way get more than he gives. Hence he will refuse to part with an additional unit for a smaller sum than its production adds to his expenses. He also will tend to operate right up to this marginal point where the last unit supplied only just brings in the incremental cost of producing it.

The whole position may be summed up by considering a state of approximate equilibrium as between consumer and undertaking. The consumer decides to take and the undertaking to sell one additional unit. The price paid for this is then governed by an upper and a lower limit. The upper (or consumer's) limit is the value of the extra service rendered by the additional unit. The lower (or producer's) limit is the extra cost due to supplying the additional unit. The price must lie between these limits, and in general the consumption will tend to expand until the two limits coalesce. When this occurs, the price of the unit = incremental satisfaction to consumer = incremental cost to producer. By incremental satisfaction is meant the money value of the additional service rendered by the extra unit, assessed by reference to the alternative cost of equivalent satisfaction. By incremental cost is meant the amount by which the costs are increased on account of supplying the extra unit.

It is natural for supply engineers to regard the problem chiefly from their own side, and to lose sight of the essentially dual character of the transaction. It is important, therefore, to emphasize that the reciprocal relationship outlined above will always determine, if not the fact, at least the extent of electrical utilization. The apparent freedom of the monopolist supplier to fix his own figure obscures the equal freedom of the consumer to reject this figure. It is true that the seller decides the

* The Polytechnic, Regent Street, London.
† *Journal I.E.E.*, 1938, **83**, p. 823.

price, but the buyer decides how many units shall be bought at this price, and in the future his will be increasingly the final and operative word on the matter.

It has been a comparatively simple matter to sell a basic minimum of electricity to any householder who has wiring facilities, but in order to sell additional units for lower-yield purposes it is necessary to give value for money, not merely over the whole transaction but on the additional units. Electric supply development may be said to have passed the " basic " stage, and is now concerned largely with the marketing of these additional units. The next stage of development will undoubtedly be spent in exploring these marginal fields, and this will require a very fine computation of incremental costs and incremental utilities. The possible contribution of superimposed control to this exploration forms the subject matter of the present paper.

TARIFF STRUCTURE: DUAL ASPECTS

It is important to distinguish two elements in a tariff, namely its form or structure and its size or magnitude. It will also be convenient to differentiate between the two aspects mentioned above, namely the costs or producer's aspect and the utility or consumer's aspect, even to the extent of putting them *vis-à-vis* as alternatives. It may be thought that the mere fact of a sale having been effected means that both aspects have necessarily been concerned. But this concern touches only the magnitude of the tariff, not its form.

When a unit changes hands under free conditions the price magnitude must, as already explained, satisfy both costs and utility values. But the form in which the price is expressed—i.e. the tariff structure—by no means necessarily complies with both these elements. On the contrary, usually it outstandingly represents one or the other and not both. The following discussion concerns chiefly the form of the tariff; and the two aspects of the problem, namely costs and utilities, are sharply differentiated in order to clarify the issue as much as possible.

The ideal tariff structure would be one that reflected both costs and utility, and this ideal is hard to realize. In the case of a raw fuel such as coal the costs of supply are mainly a function of the tonnage, and the utility value is also proportional to the weight. A flat rate per ton is then the obvious form of tariff, and the only argument which arises is as to the magnitude of the rate. But with electricity the costs are not proportional to the kilowatt-hours or to any other single quantity, whilst the utility depends entirely upon the purpose for which it is used.

The tariff designer has therefore a difficult if not impossible task in reconciling the divergent points of view of producer and consumer. Apart from the divergence regarding magnitude (common to all sales whatsoever, since all buyers tend to want things cheap and all sellers to want them dear) there is this divergence regarding form. The form in which costs naturally fall is not that in which utilities can be expressed: costs and utilities are related to different things, and neither is simply related to kilowatt-hours. The position is rather that of some fuel like petrol but of variable specific gravity being bought by the ton and sold by the gallon on a tariff which must be appropriate to uses ranging from cigar lighters to car propulsion.

COSTS AND UTILITIES

The facts as to costs are well known, and can be stated almost in a sentence. Making a careful analysis of the supply costs to the final consumer, starting with generation on the basis of Leaflet 1015* and adding transmission and distribution costs on a similar basis, it is found that just one-eighth of the total expenses are proportional to the kilowatt-hours, and the other seven-eighths are fixed costs.† These fixed costs are independent of the consumption but are in some way dependent on the demands and liabilities which result from the consumers' connections.

The facts as to utility values are somewhat less simple. It is necessary to distinguish between different loads, or at least between the two major groups recognized by the Commissioners, namely domestic and industrial. In domestic utilization the outstanding feature is the division into high-yield or unique values, and low-yield or common values. For lighting, cleaning, wireless reception, etc., electricity has no near competitors, and private electricity generation is usually not feasible. On the other hand, for most heating purposes there are a number of close rivals.

Taking the nearest alternative in urban areas, namely gas, compare gas lighting and heating with electric lighting and heating. It will then be found that if gas has a flat price throughout and if gas heating is exactly competitive with electric heating, electricity for lighting can be priced at 8 or 10 times as much as electricity for heat and still be competitive with gas.† Defining utility value as the satisfaction price, evaluated by reference to alternative means of satisfaction, it may be said that the utility value of electricity for lighting is some 8–10 times its value for heating.

In the industrial sphere there is no such wide range of use values. The chief competitor here, at least in new factories, is not some other form of power supply but rather some other source of electricity, namely private generation. The chief competition factor then is that large factories can generate more cheaply than small.

EXISTING TARIFFS: PRACTICE AND TRENDS

The following short survey covers only the two major groups, namely domestic and industrial. Together they account for over 90 per cent of the units sold and of the revenue received from sales. But it will be realized that these classifications are very broad ones, calling for much greater subdivision. Thus the " lighting and domestic " group actually includes three distinct classes of load, namely domestic lighting, domestic heat and power, and commercial lighting and heating (shops, schools, offices, etc.).

The two chief domestic tariffs are flat rates for various different purposes (lighting, heating, etc.), and all-in tariffs with a fixed charge and a low running charge. Both these tariffs may be described as representing utility values rather than costs, although at first sight the all-in tariff appears to resemble the Hopkinson maximum-demand (m.d.) tariff. Actually, however, the fixed charge (based on house size) is a measure of the probable high-yield or lighting consumption rather than a measure of maximum demand. The demand is governed far more by the use or non-use of electric cooking, water heating, etc., than by the house dimensions or rateable value.

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* Statutory Rules and Orders, 1929, No. 1015, issued by the Electricity Commission (obtainable from H.M. Stationery Office).

† See D. J. Bolton: " Costs and Tariffs in Electricity Supply " (Chapman and Hall, 1938).

The two chief industrial tariffs are the block rate and the Hopkinson or m.d. tariffs. There is some overlapping, since many Hopkinson tariffs have sliding-scale reductions in one or both parts, and on the other hand some block-rate tariffs are disguised Hopkinson tariffs in which the size of the block is not a fixture but varies with the maximum demand. Omitting this overlapping, these two may be said to divide the industrial field fairly between them, the block rate being slightly the more popular of the two.

The block-rate tariff makes no pretence of following costs, and is purely a reflection of the differing competitive powers of small and large industrialists. The Hopkinson is ostensibly a "costs" tariff designed to cover the exact expenses of supply according to the individual consumer's load-factor. Actually, the correspondence with costs is by no means so complete as it appears, owing to the fact that individual diversities differ almost as much as (and often in opposite directions to) individual load-factors. This point is discussed more fully below, and in the meantime it will be noted that the Hopkinson tariff is evidently limited in its cost representation since it gives its biggest rewards to the 100 per cent load-factor consumer rather than to the off-peak consumer, and it charges the same to those who consume during the night as to those who consume during the day.

The conclusions of this survey are that the form of British tariffs is for the most part a reflection of utilities rather than costs, and in hardly any case does it reflect both. Only one out of the four major tariffs enumerated above is in a "costs" form, and even here the cost representation is largely vitiated by ignorance of diversity behaviour and of when the peak is to fall. Moreover, the invidiousness and manifest unfairness of charging £5 or so per kW for a demand which is very unlikely to swell the system demand appreciably, makes such a tariff highly unpopular with the small power user, however useful and acceptable it may be for bulk and large-scale users.

It is extremely difficult to establish a point regarding the trend of tariffs. There are, and long have been, some hundreds of tariffs in use in this country, although many of these are statistically unimportant either through being offered by very small undertakings or through being accepted by very few consumers. Any opinion must therefore be a purely personal and very tentative one. However, the author has made a number of surveys of existing tariffs in this country, the latest of which is contained in his recently published book,* and his own impression is that tariffs have tended to move away from, rather than towards, a cost form. At least, they have not moved noticeably towards a cost form.

Fifty years ago Dr. Hopkinson announced a costing principle which was so obviously sound and just that it must have seemed that sooner or later all tariffs would inevitably come round to this form. In fact, the results have been quite otherwise. In the domestic field (the largest in value, though not in magnitude) the Hopkinson tariff is almost unknown, although it was fairly common 20 years back. In the industrial sphere it occupies something less than half the field: only for commercial loads has it noticeably extended. There would appear to be some fatal "flaw" in the m.d. tariff, not obvious on the surface.

The question raised in the present paper is: Can the technique of superimposed control do anything to bridge the gap between costs and utilities? Can it, without interfering with the proved popularity and "utility" representation of the existing forms, modify them in the direction of closer cost representation? The question will become a very vital one if we are to widen our net and try to bring in the various border-line cases that fringe our present load boundaries. Perhaps the question will be better understood, and even partially answered, if we concentrate for the moment on a single example, the Hopkinson m.d. tariff, and study its weaknesses and possible improvements.

HOPKINSON-TARIFF WEAKNESS

Superficially, the Hopkinson m.d. tariff appears almost ideal, both as a means of representing costs and in its "promotional" character (as a means of inducing consumption of a kind which costs least to supply). A certain fraction of the costs (about 12 per cent on the average, or perhaps 20 per cent for industrial loads) is dependent on the kilowatt-hours and is covered by the running charge of the tariff. The remainder are "fixed" costs, largely dependent on the size of plant and equipment employed, and these are covered by the fixed charge. If this charge is based on an actual metered reading of kW demand, the whole scheme would appear to be absolutely scientific and watertight, without any fissures of empiricism or guesswork. Is its failure to "sweep the board" due, then, merely to its unpopularity on the consumption side, or is there some flaw in its cost science? If, as the author thinks, the latter is the case, can this flaw be mended by means of superimposed control?

The fundamental weakness of the Hopkinson tariff, when applied to the single final consumer, is that it provides for differences of individual load-factors but not for differences of individual diversity-factors. The latter affect the costs of supply just as much as the former, and, moreover, they are likely to furnish just as wide a range of individual differences. Another way of putting the same thing is to say that load factors differ in kind as well as in magnitude, and a tariff which takes account purely of magnitudes is only valid for consumers who are all of the same kind. As regards consumer load-factors, magnitude *per se* is no guide to supply costs: if it were, the least cost would occur in supplying a 100 per cent load-factor consumer, whilst a consumer taking a uniform current from 8 p.m. to 8 a.m. would cost the same to supply as one taking from 8 a.m. to 8 p.m.

It is necessary to repeat these elementary facts because costs are so often regarded as a definite function of load factor, and this is certainly not the case if one is speaking of the individual consumer's load-factor. Costs are strictly related to *system* load-factor, but as regards the individual consumer a more correct statement of the position would be to say that the cost of 1 kWh is strictly dependent on the time of day of its consumption. It is true that the exact time of system peak is not predictable, and may vary from year to year over a considerable range. But ignorance of the law is no excuse for neglecting it; and the fact remains, however difficult to act upon, that 1 kWh consumed at the time of system peak costs from 5 to 10 times as much as 1 kWh consumed at a time when it cannot possibly increase the system demand.

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* See "Costs and Tariffs in Electricity Supply" (Chapman and Hall, 1938).

The proof of the reciprocal connection between load and diversity factors can be seen from the load curve. When there are a number of industrial consumers having similar working hours and under daylight conditions, the aggregate load curve is usually approximately rectangular and flat-topped, with a midday trough and a low level throughout the evening and night. That is to say, there is no marked tendency for the loads to come on at any one time more than another within the working period. The daily load factor of such a curve may be of the order of 30 to 40 per cent, though the yearly factor will, of course, be lower. Under these circumstances it is almost immaterial to the undertaking whether the individuals composing the group have load curves of the same kind as the aggregate curve (and load factors of, say, 20 to 30 per cent) or whether their loadings are very peaky, with load factors of 5 to 10 per cent. For the aggregate curve shows that these peaks average out; or, in other words, that low individual load-factors are balanced almost exactly by high individual diversity-factors. For concerns which are all operating within the same band of factory hours there is no appreciably greater cost in supplying a consumer with a 10 per cent load factor than one with a 30 per cent factor, although on a tariff of £5 per kW plus ½d. per kWh the former will pay twice as much per kilowatt-hour as the latter.

In fact, it may be stated categorically that, with any connection whose diversity is likely to exceed (say) 1¼, no tariff which neglects time-of-day can be regarded as in any way representative of costs. The Hopkinson tariff is valid as a cost vehicle only under two sets of conditions: (*a*) when the consumer's load curve is of the same shape as that of the system (i.e. when diversity is small, as in bulk supplies); or (*b*) when the consumers' load curves are all of the same general shape and differ chiefly in time extension (as with commercial loads).

It should be noted that the diversity variations which go so far to invalidate the Hopkinson tariff as a cost vehicle arise as the result of connection to a common supply. But if the single individual decides to generate for himself he gets no advantage from such external diversity, and his peak requirements and fixed costs will be strictly determined by his own maximum demand as it would be metered at his incoming terminals. Hence arises the paradox that the Hopkinson tariff fails in its aim of representing costs of supply, but (through reflecting alternative costs of private generation) it succeeds where it does not try, in representing utility values in the competitive market. Unfortunately it does not (except very indirectly) take account of the other great competitive factor, namely differences in size, which the block-rate tariff boldly recognizes.

The position in the industrial field is, then, that neither the Hopkinson nor the block-rate tariff represents costs at all closely. They are, in fact, if not in intention, " use value " tariffs, and reflect the value to the user rather than the cost to the producer. For the most part this is not a serious matter. In the author's opinion, costs are important chiefly as a means of defining the lower limit rather than determining the tariff form. In other words, it is the undertaking's task to get what it can where it can, and to use the surplus to develop fields which are at present unremunerative. It is no part of its task to make every tiny portion of the system self-supporting, even if it could always calculate (as it so rarely can) the exact share of costs for each portion.

But cases do arise, and will do so more often in the future, when this discrepancy between the costs and the tariff form becomes a serious matter. When the price has to be cut, in order to secure some load on the margin of profitability, this discrepancy of form means that there can be no nice adjustment of the magnitude. The lack of focus then blurs the edges of the bargaining picture, and it is for such cases that the following suggestions are made.

IDEAL INDUSTRIAL TARIFF

The ideal form of tariff would be one which accurately represented both costs and utilities. At the same time, any tariff to be used in a well-developed system should be generally similar to those already employed, both in order to avoid drastic changes and because the facts of existing practice are the best guides to the probable popularity and feasibility of any fresh proposals.

Utilities are best represented by a block-rate tariff, and this type is actually the most popular single tariff at present employed. It should be as simple as possible, with not more than three blocks, the final price being one-half to one-third the first block price. The actual magnitudes might have to be varied to suit the costs and the competitive position, but the figures suggested below are present representative values for the country as a whole.

The weakness of the above tariff as it stands is that the charge is levied solely on kilowatt-hours, to which only one-fifth to one-eighth of the costs are directly proportional. It is so glaringly divorced from costs that it can only be applied comparatively crudely, and can never secure the border-line loads of the future.

The Hopkinson tariff, on the other hand, is perfectly sound and watertight on the costs side, provided due regard is had to the time at which the maximum demand occurs. The author's suggestion, in brief, is that the block rate just mentioned shall form the running charge of a two-part tariff, and that there shall be in addition a fixed charge for demand, metered only at certain specified times of day and year. This would involve some sort of superimposed control, and it would also involve the undertaking being able to decide what were the times during which the peak *might* occur. In order to crystallize the matter, the following is put forward as a possible tariff of this kind:—

1½d. per kWh for the first 1 000 kWh per annum,
1d. per kWh for the next 9 000 kWh per annum,
½d. per kWh for all additional consumption (beyond 10 000 kWh),

plus a fixed annual charge of £5 per kW for all demand occurring between 4 p.m. and 6 p.m. during the months of November to February inclusive.

Such a tariff, suitably adjusted to local conditions, could be made perfectly competitive and attractive to consumers, who could very rarely generate more cheaply themselves. The final rate could, when necessary, be brought down to only just above incremental running costs, since the undertaking is absolutely covered on peak charges. Meanwhile the consumer need only bother about his maximum demand at the times when it really matters, these times being approximately one-twelfth of his total working hours. Power-factor costs could be covered by basing the fixed charge on kVA instead of kW, since the great majority of power-factor expenses (including the grid charge) are in the nature of fixed costs. Reactive consumption at other than peak times is relatively unimportant.

With the usual m.d. tariff, consumers frequently fit tell-tale indicators, bells, etc., to warn them when the demand is being exceeded; whereupon they go to considerable trouble to shut down unnecessary motors and plant. But since this may occur at all sorts of different times in different factories, the net effect on the system of all this trouble is frequently negligible. The effect of the tariff outlined above is that the consumer's trouble is enormously reduced but made much more effective. He rarely has to take steps to reduce his demand, but when those rare moments arrive his steps really do some good. Alternatively, if no steps are taken, the load curve will not be levelled but the undertaking will be correspondingly remunerated. So far as the author has been able to ascertain, such a scheme has never been tried or even proposed before, but recent extensions of superimposed control would appear to make it a perfectly feasible proposition.

NOTE ON METERING

The normal Hopkinson tariff based on kW demand involves the following: (*a*) A Merz attachment to the energy meter. (*b*) A time switch. At periodical intervals, such as $\frac{1}{2}$ hour, the time switch breaks contact and then makes again, thus allowing one portion of the demand mechanism to return to zero and come into mesh once more. Under the tariff now proposed, in place of (*b*) each meter would have a relay responsive to the superimposed control. There would be one time switch only, at the transmitting station, and this would perform its functions every half hour as before, but only during the 4 p.m.–6 p.m. periods specified in the tariff. Thus the consumers' meters would record demand only at the times and for the periods desired by the distribution engineer.

There is no need for this time to be the same throughout the system. If the peak on a certain cable or substation is liable to be a morning one, the consumers in this area can be quoted accordingly, and the superimposed message can be sent out on this line at the appropriate time. Moreover, the system is perfectly flexible, and if load conditions altered the times could be changed, by agreement with the consumers, without any change in the equipment whatsoever. A pilot lamp could be embodied in the installation showing when the demand metering was operating. The extra cost of such a system over that of a normal m.d. metering system would therefore be the difference between the cost of the relay and that of a time switch. In addition there would be the installation costs of the central control system, if this were not already installed for other purposes.

It will be noted that for the purpose of the tariff here proposed it would not matter in the least when the peak occurred, provided only that the approximate time was known beforehand. It might appear that ignorance of this time would vitiate the whole scheme, but actually all that is necessary is that there shall be considerable known periods when the peak is *not* liable to occur. For example, the grid-tariff demand is only metered during the four winter months, November to February, and with any undertaking having an appreciable power load the system peak is almost certain to occur some time between 8 a.m. and 6 p.m. on one of these four months. Even without any further knowledge, this leaves over five-sixths of the year during which it cannot possibly occur.

In a purely residential area such as a dormitory suburb the position may be more difficult, since domestic timetables are more erratic than factory hours. But, even here, conditions do not change so rapidly as to make a fairly accurate yearly forecast impossible, and in any case the above proposals are only put forward for the industrial load.

It will be noted in conclusion that there is no technical reason why the above suggestions could not be carried out without superimposed control, using only a more elaborate form of time switch on the consumer's premises. The advantage of superimposed control for this purpose lies in its greater flexibility, and probably greater reliability and absence of maintenance. Its comparative cost would depend entirely on whether there are other uses for the same system, such as street lighting control or load-levelling on the lines described below.

DOMESTIC PROPOSALS

It may be assumed that the all-in type of tariff with a fixed charge based on house characteristics is now so firmly entrenched in this country that it would be a waste of time to attempt to dislodge it. It represents use values very closely, and has proved generally acceptable to the consumers and capable of building up a large and growing non-lighting load. Moreover, in spite of its deficiencies as a cost vehicle, it can usually be priced down to the point where it is fully competitive with other sources without any risk of proving unremunerative to the undertaking. But, whilst the all-in tariff remains the centre of the attack, there is no reason why it should not be flanked by other tariffs of a special character.

Briefly, the aim of an undertaking should be either to avoid peaks or (where they must occur) to get paid adequately for them. Superimposed control may help in either of these aims. It may be used either to switch off unessential plant, thus avoiding peaks, or to change the metering so as to recover their costs. The latter possibility has already been dealt with in the case of industrial tariffs, and the former is more appropriate to the domestic situation. It will be realized that these two aims are inter-related; since, wherever there is a tariff penalizing peaks, there will be a tendency for consumers themselves to switch off unnecessary apparatus. It will further be noted that some classes of load simply cannot afford to pay for any appreciable peak incidence, so that only the one possibility is open to them.

The chief contribution of superimposed control to the domestic situation in this country would therefore appear to be of a supplementary nature. Whilst the all-in tariff remains in possession of the major part of the field there are many fringes of a marginal character which it cannot hope to cover, and it is for these that an off-peak rate should be quoted.

It is possible to distinguish two distinct phases of domestic development, and possibly we are now entering upon a third phase. The first phase reaches its completion when every householder is an electricity consumer. The next step is to get these same householders off a purely "lighting and wireless" basis and on to the heating and cooking spheres of consumption. But when this second stage is completed, and every consumer is on a two-part tariff, there still remain many possible fields unreached.

The immediate practical limit to the two-part tariff appears to be a running charge of about ½d. per kWh. Very few undertakings have been able to quote lower than this for all-day all-the-year-round service, and with coal prices rising to offset generation economies it is difficult to see how loads with an appreciable peak incidence can be quoted much lower. At this figure, electricity is fairly competitive with gas for cooking and moderate water heating, but has difficulty in competing with raw fuel for larger-scale water and space heating. The next phase may well prove to be a wholesale attack on some of these latter loads.

A general reduction of the running charge below about ½d. per unit is risky economically unless the fixed charge is unduly high. It is also unnecessary commercially for most of the services now covered. There is no point in lowering the price for a load which has already been secured, or is well on the way to being so. A preferable plan is, therefore, to leave the existing tariffs as they stand, and, without disturbing or irritating the consumer with complicated changes and explanations, merely to offer him some additional units at a cheap rate for special purposes. The terms would include the liability of an interruption of these units for a maximum of, say, 200 hours a year and for not more than 2 hours consecutively. There seems no reason why 3 units a penny should not be offered for a service of the above kind, or 4 units a penny for a purely night service. This could be put forward as a simple flat rate for commercial loads such as office heating, or as a supplement to the two-part tariff for domestic loads. In the latter case it might be necessary to charge a rent or to increase the fixed charge in order to cover the cost of the relay.

INSTALLATION ECONOMICS

Apart from special tariffs, the following is a discussion of when it would pay to put in a relay in order to reduce peak demands. Let it be supposed that the relay costs £3, and that it is desired to cover its cost in the first 6 years of operation. This means that a sum of 10s. per relay must be debited each year. Consider a proposal to fit relays to water heaters of 1-kW loading. The existing tariff is probably based on the assumption of a diversity factor of 4 or 5, i.e. there are 5 heaters on the mains for every 1-kW increase in the system demand. By fitting relays and cutting out during the peak period, this diversity is changed from 5 to infinity; so that, for every 5 relays installed, there will be a saving of 1 kW in the maximum demand.

The annual cost of the system kilowatt will probably be of the order £12 to £15, since it occurs at the far end of the domestic distribution network. Hence five relays will save at least £12, and will cost not more than £2 10s. per annum—a very substantial saving. Some of this margin, however, may have to be distributed to the consumer as compensation for the restriction in service, or in the form of a special tariff as outlined above. The calculation also assumes that the central installation is already in being for other purposes, such as street lighting control: otherwise some share of this cost must also be debited.

The above calculation may appear to take an unduly conservative view of the position, but it is well not to claim too much in the first place or to make the mistake of counting certain gains twice over. Many loads have already been contracted for (such as thermostatically-controlled space and water heating) which can only be remunerative on the assumption of a fairly considerable diversity. Assuming this to be sound, it follows that there is a correspondingly smaller gain to be obtained from off-peak control. In view of the cost both of the central control equipment and of the individual relays, it would therefore appear that the installation is likely to be justified (on peak-saving grounds) chiefly in the following two cases: firstly, when the load per relay is fairly large (say, several kilowatts); and secondly, when the existing diversity is small, so that apparatus which is not so controlled is fairly likely to come on to the peak.

This last point discloses something of a dilemma. Unfortunately one cannot have it both ways. Either the existing installation is likely to come on during peak times, in which case an interruption at these times is liable to cause appreciable hardship, or else it is at present not likely to overlap the peak, in which case there is so much the less to be gained from off-peak control. This dilemma appears to suggest the need for some radical changes in the design of consuming apparatus.

CONSUMING APPARATUS

Most of the services rendered by electricity, including almost all the lighting and motive power, are immediate in character and cannot be either stored or waited for. The consumer cannot easily vary his times of utilization, and it would be a profound mistake to attempt to make him do so. Any conscious restriction, or any tariff which makes him glance apprehensively at the clock or the meter, is psychologically bad, and is liable to have a serious inhibiting effect on his actions and his consumption. What is needed for our purpose is apparatus which will give the consumer all the service he requires, and yet which is capable of "free-wheeling" for an hour or two at the bidding of the authority and preferably without any indication to the user. No attempt will be made here at a review of apparatus; merely an indication will be given of the kind of thing which is needed, and the probable lines of future development.

The obvious directions in the domestic and commercial field are space and water heating, although something is also possible in the way of storage cookers. In all three cases the problem is linked up with the question of the difficulty of finding room for the necessary equipment. Now that a large proportion of the population lives in small flats or divided houses, the provision of space for apparatus even with semi-storage characteristics is increasingly difficult. However, the search for suitable materials is being actively pursued, and one requires no special inside knowledge to predict speedy developments. Inventions, nowadays, are rarely isolated phenomena but are more in the nature of social developments, appearing at a number of points simultaneously when the need arises. Now that the technique of superimposed control is well established, a parallel development in the appropriate consuming apparatus may therefore be expected to follow.

RECAPITULATION

In case the suggestions of the present paper appear to be unpractical and far-fetched, it will be well to conclude by recapitulating certain facts.

(1) Only about one-eighth of the mean costs of supply are dependent on kilowatt-hours, and with a mean station load-factor over the country of 34 per cent there is still enormous scope for cost reductions through improvement of this load factor.

(2) This improvement is not likely to occur automatically. Over one-third of the country's houses still remain to be wired, and the first requirements of these new consumers will be such basic needs as lighting. This growth is likely to neutralize the effect of the growth in diversity of the existing connections, as evidenced by the fact that the country's mean load-factor has scarcely altered over the last 10 years.

(3) The improvement of individual consumers' load-factors through the medium of such things as current limiters, load levellers, and plain m.d. tariffs has comparatively little effect on the system load-factor. Through failing to discriminate between peak times and other times these devices merely reduce the consumer's diversity to almost the same extent that they improve his load factor. They produce the maximum inconvenience to the consumer for only a fractional gain to the undertaking.

(4) Every kilowatt at the disposal of the undertaking at the far end of a distribution system is worth some £10 to £15 a year. That is to say, 1 kW at peak time costs this sum, and conversely every kilowatt avoided then will save this amount. The fact that the kilowatt in question is in the consumer's premises makes it all the more valuable, since it also saves voltage-drops. Provided they are at the full disposal of the distribution engineer, it is just as useful to have 5 000 1-kW loads at the end of the line which can be switched off at will as to have an extra 5 000 kW in the substation and power station.*

(5) Present tariffs, in their structure at least, are based almost entirely on use values rather than cost of production. They have served fairly well, and will continue to do so in those fields where electricity has natural advantages, but are likely to fail in the more difficult fields. Now that the cream of the load has been secured we are looking for some method of making a further living out of the skim milk, and superimposed control is one such method. The proposals put forward above can be briefly summarized under two headings—industrial and domestic (plus commercial).

The industrial load, although less important economically, still accounts for considerably over half the total units sold, and it has enormous future potentialities. In fact, only about one-third of the total factory power of the country is at present supplied from public mains. But much of the remainder comes from old plant whose capital charges are negligible, and such a load cannot be secured without very close pricing. A tariff (such as the block rate) based on kilowatt-hours, on which only one-fifth of the costs are dependent, is altogether too crude for the purpose. The margin of error is so great that either the price is too high to secure the contract or else it runs the risk of an unremunerative peak incidence. The normal two-part tariff is only a little better. The running charge can be scientifically assessed, but the fixed charge is often made higher than it should be through sheer ignorance of the individual diversity and of when the maximum demand actually occurs. Close quotations necessitate exact costing, and the ideal tariff will have a stepped running charge and a fixed charge on a time-of-day basis.

In the domestic field, most of the high-yield loads have been secured or are on the way to being secured by means of a "use value" tariff, and at prices which do not require very fine cutting. The low-yield loads, on the other hand, will frequently not stand any peak charges whatever, and the only alternative then is to keep them off the peak. For domestic and commercial loads the suggestion is to supplement existing tariffs with a cut rate for special purposes, and with a supply which is liable to limited but unspecified interruptions.

FOREIGN EXPERIENCE

Although the main purpose of the paper has been to make suggestions and to explore possibilities, it is extremely desirable to check these as far as possible by reference to the facts of practice and experience. Unfortunately, there are very few time-of-day tariffs employed in this country, and, so far as the author is aware, no example of the use of superimposed control for this purpose. There are a number of examples abroad, particularly in France, but these are not necessarily relevant to our own situation. In the matter of tariffs one is dealing with personal reactions, habits, modes of living, and differences of tradition, which are liable to upset any international generalizations. However, it is proposed to append, for what it is worth, a short account of French experience on these lines.

Time-of-day tariffs operated by superimposed control are in use in a number of the larger French towns, including Paris and Versailles, and in Brussels. The following are the details of the Paris tariff for lighting and domestic supplies. Consumers fall into two groups, according to size, only the larger ones being eligible for the time-of-day tariff. The size is defined by the maximum power consumption in relation to the number of rooms, namely 2 kW for a 1-room apartment, 3 kW for 2 to 4 rooms, 4 kW for 5 to 6 rooms, etc. Consumers whose power demand is equal to or less than this amount are supplied through a single-dial meter, and are charged at the following rate: First block at 3·0d. per kWh, second block at 1·6d., remainder at 0·54d. The size of the first block is dependent on the number of rooms, and the second-block size is always half the first-block size.

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* This assumes that these loads would actually be in service at the peak time. Otherwise this statement must be qualified by the concept of diversity, as already explained.

Larger consumers, namely those whose power demands exceed the figures given above, can have supplies on a two-part tariff consisting of a small fixed charge to cover lighting consumption, and a running charge varying with the time of day. The fixed charge depends on the number of rooms, and ranges from 11s. to £2 a year for a 1- to 6-room apartment. In addition to this fixed charge, all the energy passes through a special meter having three registrations. These are put into operation at the appropriate times of day by means of tuned relays on a centralized control system. The prices and times can best be illustrated by means of a diagram (see Fig. 1).

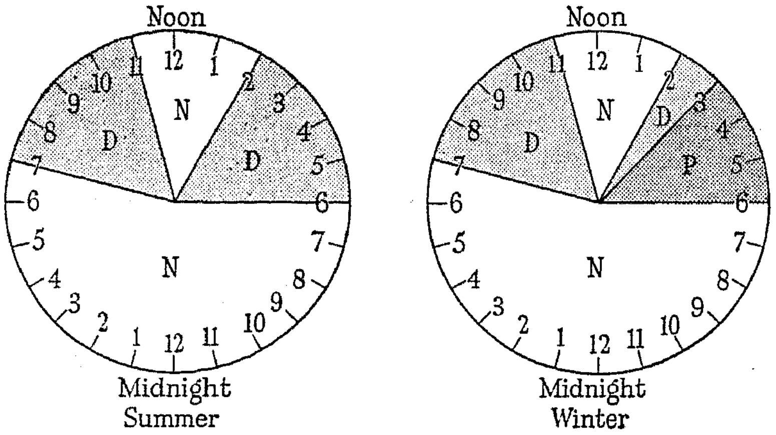

Fig. 1.—Paris tariff.

P = peak period, 3–6 p.m. in winter, price 2·5d. per kWh.
D = day period, 7–11 a.m. and 2–3 p.m. in winter or 2–6 p.m. in summer, price 1·3d. per kWh.
N = night period, all other times, price 0·53d. per kWh.

In Paris the time-of-day tariff started in 1924 as a special rate for off-peak consumption, and it has since been developed into the three-rate tariff outlined above. It is difficult for an outsider with a purely superficial acquaintance to pronounce upon the operating results, but it would appear that the tariff is not a conspicuous success in the purely domestic field. Less than 1 per cent of the Parisian consumers make use of it, the exact figures being 6 300 out of a total of 860 000. There is, however, a definite and growing utilization of it in the commercial field for large-scale cooking, oven heating, and thermal storage. Moreover, in the past, domestic development on this tariff has been cramped by the fact that only the larger installations justify the cost of the special metering. This position may at any time be modified by improvements in the technique of superimposed control.

Summing up, the Paris results appear to lend general confirmation to the opinion expressed in this paper that for Great Britain the normal domestic uses are adequately catered for by our existing types of tariff. The function of a time-of-day tariff in the domestic and commercial field would be to develop new loads not yet reached. It should supplement rather than supplant existing methods of charge.

NOTE ON NOMENCLATURE

Standard nomenclature on tariffs is extremely meagre and unsatisfactory. Not only are several of the more important tariffs (such as the block rate) not defined in the " British Standard Glossary of Terms Used in Electrical Engineering,"* but in the case of others the names allotted are open to serious objection. The tariff chiefly concerned in the present paper is that in which different prices are given at different times of day. There may be two, three, or more different prices—e.g. in Paris there are three. The official name for this is the " two-rate tariff," which for obvious reasons is unsuitable here. The term employed here is " time-of-day tariff," which is at least precise and fairly descriptive.

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* B.S.S. No. 205—1936.

† This Bibliography has been kindly supplied by Mr. J. Gourio, of the Union d'Électricité, and is reproduced by his permission. The references have, as far as possible, been checked by the author, but in a number of cases the literature is not available in this country.

DISCUSSION BEFORE THE TRANSMISSION SECTION, 10TH MAY, 1939

Mr. J. M. Kennedy: It is dangerous to say, as the author does, that the last unit is supplied at only the incremental cost; because a time comes when one finds one's cables are loaded up and one has to lay out additional capital in order to supply further units, whether peak-load units or not. The nearer the consumers' or upper limit approximates to the sellers' or lower limit, the less the chance of future development of sales at the price the consumer can afford to pay. On page 329 the author attempts to define " incremental cost." It is very difficult to find out what the term really means, and in this connection many of us remember a somewhat argumentative paper by Woodward and Carne,* who went into the matter in great detail.

I think the author is unduly critical of the seller of electricity when he says that all buyers want things cheap and all sellers want them dear. That is rather unfair to suppliers, many of whom are extremely progressive in their ideas. Their whole object is to try to reduce the cost of energy within the financial limits imposed and so induce greater sales.

Turning to the section headed " Costs and Utilities," I agree that costs are well known so far as the figures are concerned, but the question is how to interpret the figures. The author refers to the Commissioners' Leaflet 1015; this was not put forward for the purpose for which he has been using it, but only for the purpose of adjusting the known station costs to load factors, thus enabling one to ascertain from any given set of conditions and output what the increased or decreased costs would be for more or less units. He also says that all distribution costs are fixed costs, and that they can therefore be added to the fixed costs arrived at on the basis of Leaflet 1015. I agree that if one does that, one arrives at figures such as he refers to. Of the revenue earned for the last year for which we have the figures, some £92 000 000, the fixed costs are about £76 000 000 (86 per cent, as against the author's figure of 87½ per cent). But what does that really mean? It does not mean that if one can save a kilowatt at the time of peak load one can deduct its value from the total of fixed charge. Once the system has been laid out, if one can induce a consumer to take off 1 kW of demand on peak load the only saving is the basic cost at which one is buying from the bulk supplier, probably £2 10s. or £3, but not £10 or £15 as the author suggests.

I am not quite sure how far he approves of the Hopkinson tariff. One of its many flaws is that it does not take into consideration the fact that as regards distribution costs it is much cheaper to have one consumer buying 1 000 kW than to have 1 000 consumers each buying 1 kW. There is also the psychological objection to the Hopkinson tariff, especially from the industrial consumer's point of view, that the fixed charge has to be paid even when no use is made of the supply for a period of, say, a month. The result is that many suppliers have had to depart from the Hopkinson tariff and charge a slightly higher amount per month. Some commercial users are so opposed to the Hopkinson tariff that the undertakings have had to change over to the block tariff.

Does the author really mean that only those consumers who take a supply at the peak periods should be charged a proportion of the fixed cost? The fixed charges, he states, amount to £12 per kW, and he therefore implies that consumers who take a supply at the peak periods should be charged £12 per kW. Let us look at the matter from another point of view, the point of view we have to face at the Commission so often when we are required to interpret Section 12 of the Act of 1926, and the Third Schedule, which deals with transmission charges. At the end of the Third Schedule we are told that if a transmission line is used for giving a supply to more than one person we have to determine the proper proportion of the charges to be allocated to each person supplied. According to the author the " proper proportion " is to be based on the time for which the supply is used at the peak-load period. Some transmission lines are used for giving supplies to different undertakers, who may have a high consumption in the winter and a low one in the summer, or vice versa. The man who takes the dominant supply in the summer should, according to the author, pay nothing for transmission just because the maximum demand on the bulk-supply line happens to be given in the winter. So far as the transmission costs are concerned, the only logical way is to divide them *pro rata* to the maximum demand taken by any consumer at any time.

The author refers to the possible use of superimposed control for industrial loads; I must confess that I think this almost impracticable. It is possible, however, to arrange with industrialists that certain peak loads will only come on during the night shift or at some other stated hours, and either not make a kilowatt charge at all or make a reduced charge. There are quite a number of undertakings that during the night hours charge about 30 per cent of the nominal kW charge, and other special supplies (e.g. for the heating of swimming baths) are given on a unit rate alone at a very low figure. But those are exceptional cases. Surely the use of superimposed control is only applicable to domestic premises, and even then we have to develop special apparatus suitable for use with the control equipment. In the majority of small houses it would be impracticable to install a large enough water heater to justify the introduction of the superimposed control system. Again, it is conceivable that some form of storage panel heater will develop, and if this can be installed at a price which will attract the small user, well and good. Superimposed control may be valuable for street lighting, but here a word of warning may be uttered, because, in war time, street lighting will be cut out entirely, and therefore there will be no need for control.

The author seems to indicate that the supply industry is in a rather stagnant condition. But the load factor during the last 10 years has not remained constant, it has gone up from 31·6 per cent to 36·1 per cent—not a sensational increase, but quite an appreciable one. Another point of interest relates to the number of units supplied per £ of distribution capital. Miss Noakes and I* a few years ago drew attention to the fact that this figure had been gradually falling from 1924 until 1932 but since that date it has gone up. Therefore the supply industry is perhaps not in quite such a bad way as the author thinks.

Mr. J. I. Bernard: The paper may be said to mark the transition from tariffs based on load factor to those in which some time-of-day factor is introduced. In the early days of the industry when there were only two main classes of load, namely lighting and power, the maximum demands for which overlapped, and caused a winter peak, tariffs based on load factor reflected the cost of supply quite well. The ordinary two-part tariffs were introduced, but they have in many cases ceased to represent the cost of supplying some types of load. As long as the time of the peak load in any system is fixed, usually by a preponderance of lighting and power load, it is possible to assess the peak infringement of any load in regular use and to charge accordingly for the service. Nowadays, however, the time of the peak load is becoming more uncertain. Undertakers, for example, who have highly developed domestic loads, may find the peak occurring at any time of day, particularly breakfast time, midday, and evening. It is this factor more than any other which has caused increased interest to be taken in manually-operated superimposed control, and I do not think the author has drawn quite enough attention to it.

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* *Journal I.E.E.*, 1932, **71**, p. 852.

* *Journal I.E.E.*, 1933, **73**, p. 97.

The paper stops short at the important question of the design of the consuming apparatus for use in conjunction with superimposed control. Electric water-heaters are obviously a suitable type of apparatus to be controlled by superimposed control because they depend for their satisfactory service on storage characteristics, and the provision of additional capacity to tide over a peak-load period of an hour or two is not a serious matter.

The author estimates the saving which can be made by the superimposed control of water heaters. It is admittedly a conservative estimate, but it shows a saving of approximately 48s. per water heater per annum. Of this amount the reduction in the electricity bill due to a charge of, say, $\frac{1}{3}$d. a unit instead of $\frac{1}{2}$d. is approximately 28s., so that there remains a saving of 20s. per annum which can go to pay for other increased costs. If the superimposed control system has already been provided for other purposes such as street lighting, and if no extra cost is involved on account of the larger-capacity water-heater, as may be the case when this consists of a converted tank of large capacity, the whole of this 20s. is available as increased profit to the undertaking. Savings of this kind are being considered, for example, in the town of Winnipeg, Canada, where there are more than 20 000 electric water-heaters connected, i.e. one for every two consumers on the system; and where the water-heater tariff includes a proviso that, if the supply authority wishes, the supply may be interrupted for not more than 876 hours in the year (10 % per cent of the total time), with a reduction in price of 10 % to the consumer. When the question of introducing superimposed control was examined recently, I understand it was estimated that the total cost of installing superimposed control in Winnipeg would amount to about £60 000, and that as a result of that expenditure it would be possible to reclaim approximately 20 000 kW, representing a capital cost of £3 per kW.

The author remarks that no time-of-day tariff for the small industrial consumer has yet been introduced, but I believe that a tariff of this kind which consisted of a primary charge of about 4d. per unit for all units consumed during the hours 4 p.m. to 6 p.m. in three winter months and $\frac{5}{8}$d. per unit for all energy consumed at other times was actually in use at Croydon many years ago, with great satisfaction alike to the supply authority and to the users.

In conclusion, I would support the author's plea for clearer nomenclature, and I would suggest that the term "after diversity demand" which is used quite generally in America, should be used here to describe the maximum demand of a group of appliances of similar characteristics divided by the number connected. There is no term in common use in this country for that quantity, which cannot be described as "average demand" or even as "system demand," since the latter is usually understood to relate to the demand at time of system peak load.

Mr. J. A. Sumner: I notice on page 332 the statement that "it is the undertaking's task to get what it can where it can, and to use the surplus to develop fields which are at present unremunerative. It is no part of its task to make every tiny portion of the system self-supporting, even if it could always calculate (as it so rarely can) the exact share of costs for each portion." It is a little unfair of the author to lead us to think, in the earlier portion of the paper, that the cost basis is the proper system to adopt and then, later on, to insert such a passage in his paper. Whilst I see the advantage of working on a cost basis as compared with the utility basis it is not, in my opinion, feasible to adopt the former basis. Let us consider, for instance, the case of a hypothetical undertaking with 1 000 kW of generating plant, which has two consumers, one taking 1 000 kW for 12 hours a day and the other 600 kW for the remainder of the day. Should one charge the full maximum demand to the first consumer and nothing to the second, or divide the demand charge between them in proportion to their demand? I am afraid that it is more usual to charge each for their full maximum demand.

Another point in this paper that interests me is the manner in which the author deals with the Hopkinson tariff. Some 2 years ago in a paper* which I read before The Institution I had the temerity to question the validity of the Hopkinson tariff under modern conditions, and I am pleased to see that the author supports my view on this subject. When the Hopkinson tariff was first put forward the fixed and running costs of supply were nearly equal, whereas to-day the ratio of the fixed costs to the running costs is nearly 7 to 1.

I do not think there is anything unique about the author's ideal industrial tariff. Such a scheme—a fixed annual charge per kW based only upon that demand occurring between 4 p.m. and 6 p.m. during the months of November to February inclusive—has been tried by at least three undertakings of which I have personal knowledge. I have in mind another tariff which is offered on the basis that the consumer shall only pay a maximum-demand charge if the supply is taken between the hours of 9.30 a.m. and 11 a.m. and 4.30 p.m. and 6.30 p.m. during the months of November to February inclusive.

While I have a good deal of sympathy with the author's suggestions regarding the use of superimposed control for smoothing out the demand curve, I can see many difficulties in the way. For example, it is difficult to ascertain the particular load that one can cut off at a minute's notice without meeting with grumbles from the consumer. Another difficulty may arise, in certain cases, due to the method of charging adopted by the Central Electricity Board, under which an undertaking pays so much per kW on the maximum demand of any half-hour of the day in four months of the year. Consider an undertaking which has a normal day demand peak of 15 000 kVA, and suppose that a consumer comes along and requires a load of 20 000 kVA only at night time. If it were to supply such a load, the undertaking, buying from the Board, would have its peak demand, and charge, lifted by

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* *Journal I.E.E.*, 1937, **81**, p. 429.

5 000 kVA and transferred to the night period, i.e. the off-peak supply would become the peak supply. In addition, there are those cases where the undertaking takes supply from the Board under Section 13 of the 1926 Act. The undertaking does not buy on a maximum-demand basis, but bases its charges to consumers upon it. I think that until one can deal with these difficult points, and obtain a greater uniformity of charges between undertakings, it will not be easy to extend the system of superimposed control that the author puts forward.

Prof. R. O. Kapp: Those who are concerned with tariff-making are always bound to oscillate between the two extremes expressed here—a tariff based on cost and a tariff based on utility. I am glad to see that, since the early days when I first heard papers on tariffs read at The Institution, that distinction has been so greatly clarified. This particular paper emphasizes too much the cost side of the tariff, and it is from that point of view that I want to say a word or two of criticism.

One can, of course, speak of " the bad old industrial tariffs " because they have, admittedly, certain defects. A great deal of the undertakers' revenue is obtained from consumers' maximum-demand charges which occur at times when they cost the undertaking nothing. It is, perhaps, unjust to make these people pay, but the revenue has to be obtained somehow. One can devise a tariff which abolishes this injustice but the new tariff must obtain the same revenue by other means. How, in the author's opinion, should that revenue be got? The way suggested in the paper is the tariff based strictly on cost. Under such a tariff all that revenue which we now take unjustly would be contributed by the consumers who take peak load at peak times. But such a tariff would be commercially suicidal. The kW charge would have to be very high. One might try to modify it by (i) adopting a steeply-graded maximum tariff, or (ii) increasing the unit charge; but it seems to me very doubtful whether either modification would be commercially feasible. There is a third possibility, that of making a connection charge, but that would mean making the off-peak consumers pay much the same as under the existing bad old tariff. So perhaps the bad old tariff is the best after all. I should like to ask the author whether the advantage due to the more scientific adjustment of incidence of peak-load charges would have a sufficient effect in smoothing out the load curve to justify the complication which the altered tariff, re-altered, and possibly altered again, would bring about.

Mr. C. T. Melling: The author points out that we must work on the incremental-cost basis in thinking of the final unit sold to the consumer, but, like Mr. Kennedy, I regard that suggestion with hesitation because incremental costs have a habit of creeping up, even for consumers who are already connected and loads which have already been secured. One must bear in mind the possibility of increased costs of fuel, and of requests from other consumers for lower charges if one consumer is given a tariff computed on an incremental-cost basis which is lower than other tariffs.

Referring to the consumer, the author says " He will only consume up to the point when the last unit bought gives him more or better light, heat, and service, than he can buy for this money by other means." That is not quite the case. The consumer thinks not so much in terms of money as of service, and most consumers are prepared to pay a higher price for electricity than for alternative fuels.

In applying ripple control, various schemes attractive to the consumer have been suggested, but some of them with unit charges so low as to be dangerous to the undertaking on the supposition that certain peak conditions will obtain. But instead of a peak which lasts 1–2 hours, conditions may arise which will give a peak lasting 12 hours, and this involves the extra expense of large storage heaters and the liability of a high demand immediately after the restricted period. The alternative to complete restriction is to have the restricted times at different hours for the various heaters—depending on time-switch setting or selective ripple control.

The author is pessimistic in saying that a running charge of about ½d. per kWh for domestic purposes makes electricity fairly competitive with gas for cooking and moderate water heating. Presumably he is assuming city and large-town gas prices; but in small towns and rural areas electricity is building up a substantial cooking and water-heating load at ¾d. and 1d. per unit.

Mr. H. P. Barker: The arguments commonly directed against load control by superimposed means can be divided into three classes. There are those who say it is impracticable, those who say it is uncommercial, and those who consider that it is contrary to the interests of the industry to control consumers' loads in any way. Separately, these arguments seem invalid, and to answer them one need lay down two premises only: Firstly, that the average costs of electricity in bulk can be truly represented both as to form and as to amount by the prevailing grid tariff; and secondly, that the desirability of a load-control scheme is ultimately measured by profits earned by the supply authority which they would not otherwise have been able to earn, or by losses avoided by them which they would otherwise have been unable to avoid, and/or by lower selling prices of energy to consumers.

To answer those who say that load control is impracticable, it suffices only to say that it is being progressively practised with entire success, a large water-heater control scheme now in operation in the Liverpool area being an excellent example of its practicability.

To answer those who say that it is uncommercial is a " yes " or " no " matter of arithmetic, as it has been well demonstrated that water-heating and space-heating loads can be interrupted for short periods at peak times with entire absence of inconvenience to or comment from the consumers. The resultant savings in maximum demand, which in the case of water heating may amount to about 20 per cent of the connected load, and in the case of space heating to a much higher figure, are such that the undertaking may either retain the profit or pass a part on to the consumer in the form of lower tariffs. It has been shown that consumers of this type of load are only too happy to fall in with such a scheme.

Finally, to answer those who say that such schemes are not in the interests of the industry, the reply would be that the interests of the supply authorities must lie not only in selling electricity for various services at the lowest possible prices, but also in avoiding losses due to maximum-demand charges on discrete classes of load.

It appears patently clear, to take direct space heating as an example, that there exists a very large market for this service which can only be tapped at flat unit prices of $\frac{1}{2}$d. or under. It is a matter of arithmetic to demonstrate that such prices cannot in general be economically quoted by undertakings who take a bulk supply at the grid tariff, or who accept the grid tariff as a yard-stick of prime cost.

If by any technical manipulation they are enabled to sell cheap units and thereby make electricity available to a class of consumers anxious to use it at the right price, it seems impossible to argue that in so doing they are acting detrimentally to their own interests. Costs of maximum demand being an inherent problem, there is the strongest *prima facie* case for any practicable method of ameliorating such costs.

Mr. Kennedy implied that it is impracticable to switch off consumers' motors, and I do not think that the hardiest enthusiast for load control could ever disagree. There are, however, many methods of applying the central control principle to industrial users by what may be termed permissive peak restriction, which on the one hand gives the consumer complete liberty to use his plant at peak times and bear the cost of that part of his maximum demand which coincides with the undertaking's, yet at the same time by suitable warnings permits him at his own volition to reduce his demand with his load and thereby save maximum-demand charges.

By the use of modern control technique, tariffs of this kind can be operated with a high degree of security to the undertaking and a high degree of utility to the consumer.

Mr. W. E. Burnand (*communicated*): I am particularly interested in this paper because well over 30 years ago I suggested ripple control for tariffs and the cutting-down of infrequent peaks that required reserve plant that could not be kept loaded long enough to pay. So far as I can ascertain, that was the first time such a scheme had been put forward. I began my work in this field by inventing the first real indicating frequency meter,[*] and applying the principle of this instrument to actuate distant apparatus.[†] My remote control system made use of radio waves in this case, and was to some extent the opposite of ripple control, being control by sustained pulsations in a radio output. The method of using a superposed ripple in the case of a wired system was obvious, and in 1900 I tried the effect of a small component of about 500 cycles per sec. on a part of the Sheffield electric supply system. The 500-cycle ripple was applied by a small generator at my own works, and on testing by telephone at another works a few hundred yards away, on the other side of the road, I found the characteristic "squeal" to be nearly as pronounced as at my own works. Having other more urgent work to do at the time, I abandoned the experiments.

Regarding the section of the present paper headed "Ideal Industrial Tariff," I would draw attention to an article[‡] which I wrote in 1912 advocating ripple control in connection with electric supply tariffs. I have since mentioned this scheme at various Institution discussions.[§]

The author points out very clearly the weakness of the Hopkinson and maximum-demand systems, but I think it would be as well not to over-emphasize the "time of day" part of the suggested alternatives, because conditions are altering, and with the adoption of superimposed control the "time" is likely to alter still more rapidly. Moreover, a valuable feature of this system is the great reduction in the amount of plant that needs to be kept in reserve for emergencies. It is obvious from the figures given by the author that electric supply could be greatly extended at the low charge which is possible for the extra units that can be supplied without material extension of plant, by utilizing superimposed control. The advantage of this type of control is that whatever path the ripple takes between control points, the frequency remains the same irrespective of variations in voltage, leakage, or resistance.

Mr. E. Hallowell (*communicated*): The author's academic review of basic principles of electricity supply and tariff structures is of topical interest, but to my mind he has not been successful in drawing from this review any practical proposals of real benefit to the supply industry.

With regard to the time-of-day tariff, I do not believe that a consumer will modify his habits to suit the convenience of electricity suppliers. In the great majority of instances he will continue to wash or bathe when necessary or convenient, and if, as bad luck will have it, the peak incidence is high, he will turn over to some less expensive form of heating.

Such highly competitive supplies as water heating may be made both profitable to the supplier and satisfactory to the user, if dealt with on a strictly economic basis. Firstly, energy for such supplies should be "off peak" in the most complete sense; central-station and substation demands must be individually and automatically protected so that the capital-cost component—some £10 per kW, or more than 80 per cent of the total cost per kWh—is completely eliminated. The cost of such a supply can then be determined with great accuracy, being essentially limited to the cost of fuel and rates. Secondly, having regard to the protracted "peak load" periods which such complete control will entail, particularly when the proportion of "off peak" load is high, the load should be switched off and on progressively step by step, to follow the contour of the load curve, since by so doing the average restriction period will be approximately halved and a high load factor achieved. Thirdly, so as to permit the connection of a high proportion of controlled load without inconvenience to consumers and with a minimum of thermal storage, the control should be selective in accordance with the consumer's stored-heat resources. In other words, advantage should be taken of diversity in demands for hot water, and the consumer most urgently needing supply must take precedence.

A simple ripple control system based on these principles and utilizing only two frequency channels, is already in operation on a large supply undertaking in the North of England, energy being sold at the low rate of 3 units for 1d. Restriction periods up to 4 hours in duration have been experienced during the winter months, but, thanks to the progressive and selective action of the control, have passed unnoticed by domestic consumers. A great deal of the property supplied is of the artisan type; and any other class of control, calling for higher energy rates, or additional thermal storage over and above that of the ordinary converted domestic cylinder, would be quite out of the question.

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[*] British Patent No. 26723—1898.

[†] *Ibid.*, No. 11704—1900.

[‡] "Low Rates and the Development of the Central-station Service," *Electrical World*, 1912, **59**, p. 261.

[§] *Journal I.E.E.*, 1912, **48**, p. 441; 1912, **49**, p. 166; and 1939 **85**, p. 569.

Mr. S. F. Osborne (*communicated*): In the section of the paper headed "Basic Principle of Electricity Sale" the author applies the law of supply and demand to the provision and use of electrical energy, but the methods of off-peak superimposed control referred to in the paper constitute conditions of supply (except in few instances) such that the "value" to the consumer of off-peak energy is below the limit of cost at which the producer can supply the additional energy.

The interruption of the supply for lengthy peak-load periods make off-peak energy of little value to the consumer unless a form of "selective" control is adopted, enabling the supply authority to disconnect consumers for long or short periods according to the urgency of their needs during peak-load periods. This is particularly noticeable where off-peak energy is supplied for domestic water heaters. Existing storage cylinders are not usually of sufficient capacity to supply consumers' hot-water requirements over long peak-load periods unless these requirements happen to be small during such periods. The provision of larger storage tanks is usually impracticable in working-class homes.

A system of selective off-peak superimposed control has recently been introduced and tried out with remarkable success for domestic water-heating supplies. A large number of water heaters have been connected to a system on which a maximum of 4 hours' restricted supply is necessary at the time of peak load. The disconnection of all consumers for the full 4 hours would cause considerable inconvenience to a large percentage of them, but by means of the selective action of the control those consumers who use water during peak-load periods have been disconnected for short periods only at the time of extreme maximum demand. At the end of the winter season every consumer taking the supply was interviewed, and inquiries showed that not one consumer was aware that the supply had ever been disconnected, though a number of the users were disconnected for the full 4-hour period. Recording thermographs and voltmeters installed in consumers' premises show that there was a direct relation between the duration of interruption of supply and the temperature of the hot-water supply in different premises. This method of control causes minimum inconvenience to the consumer and ensures maximum load factor for the undertaking.

The proposed time-of-day tariff is not likely to be popular, as there are few industries in which the flow of work can be adjusted according to the times of peak load on the supply authority's system. With this proposal, the supply undertaking is unable to make use of one of the important advantages of superimposed control, namely that in the event of breakdown, excess loads on any part of the system may be eliminated by the disconnection of those supplies which have a storage medium.

Mr. R. B. Rowson (*communicated*): It is significant that the author has had to assume that the cost of the injecting apparatus has already been covered by its use for such purposes as street lighting control. In the case of undertakings who have looked ahead and incorporated a fifth core in their l.t. networks for street lighting control, the position is more difficult, as the cost of the injecting apparatus has to be met by increased net revenue arising from the controlled supplies other than street lighting.

Now that several superimposed control systems are in use or in course of being put into commission, I would suggest that the electric supply industry should finance an experiment which would have considerable value in regard to the formulation of tariffs. If all, or most, of the premises with cookers installed on these networks were equipped with relays it would be possible to interrupt the supply to the cookers for short periods without inconvenience to the users. The decrease in load could be noted, and the experiment repeated at various times throughout the day and throughout the year. Full details of the number of cookers controlled by the relays would be available, and it would be possible to obtain from the results complete details of the diversity. More comprehensive results could be obtained by using three or four different frequency bands, as by this means the demand of various numbers of cookers could be measured. At a later date the same relays could be used for a similar investigation with other types of apparatus such as water heaters. What are the author's views on this proposal?

The main use of superimposed control suggested by the author is to control water heaters. I feel, however, that sufficient weight has not been given to the difficulties raised by the necessity for a fairly large tank. If the undertaking has a daily load-factor of say, 50 per cent, in the winter months it is very difficult to make the hours of cut-off short, and a 20- to 30-gallon tank is necessary. Also, the diversity between heaters which have been cut off is likely to be low when supplies are resumed, and thus the number of heaters which can be accommodated without increasing the demand is limited; as a consequence the author's statement regarding infinite diversity requires qualification.

In his criticism of the Hopkinson tariff it appears that the author has not had regard for the fact that the kilowatt charge is, in practice, often based on the summated load and not on the simultaneous load. If this were not the case kilowatt charges would be within the region of £10 to £16 per annum, instead of from £4 to £6. It is agreed, however, that there is considerable justification for metering the kilowatts during certain hours only, and this is fairly general practice. With the alteration in the shape of load curves caused by cooking, etc., it is very necessary that the period from 4 p.m. to 6 p.m. mentioned in the paper should be extended to include the morning and possibly the midday peak. Though neglecting his demand during off-peak hours sometimes helps the consumer, he is not as satisfied with the arrangement as the author appears to think, the general argument being that the 4 p.m. to 6 p.m. period is that when lighting and power demands coincide and thus is just the period when the consumer's demand is likely to be greatest.

The author also repeats his argument that a large number of low load-factor consumers are as good as a high load-factor consumer. Now since the average simultaneous demand of such a group of n consumers each having, say, a demand of 1 kW, is pn (p being the probability of a consumer making a demand at a particular interval) provided the conditions as to random use hold, it follows that there is a definite probability that this demand pn will at times be exceeded; in fact, it would appear that on 50 per cent of the intervals the total demand would exceed the mean figure. About 16 per cent of the simultaneous demands should exceed the average demand plus the square root of it, and there is just a chance, of course, that all the consumers may come on together. Though this latter chance is very remote, proof that the average is exceeded is shown by telephone exchanges becoming overloaded, roads becoming blocked with traffic, and by the increased demands of many supply authorities during December, 1938. In view of the foregoing it would appear that a group of low load-factor consumers may be a serious liability instead of the unmixed blessing that the author suggests.

[The author's reply to this discussion will be found on page 344.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 6TH MARCH, 1939

Mr. H. Pryce-Jones: The paper does not take into account the fact that the supply engineer has a considerable interest in the matter of giving good service to his consumers; nor does the author seem to realize that the electric supply industry does not possess the monopoly in the sense that he suggests. Undoubtedly, supply authorities possess legal powers and a certain degree of monopoly so far as electricity alone is concerned, but, at least so far as Liverpool is concerned, we have extremely keen competition to contend with from the gas industry.

The author says that the supply engineer, in fixing his tariff, tends to lose sight of the utility value of electricity in its various applications; but even if we would like to lose sight of it we could not do so, by reason of the existence of the competition already mentioned.

As regards the arguments on which electricity tariffs are based, it cannot be disputed that the man who takes his load in peak hours is to some extent preying upon that section of the community who take their load over a reasonably wide period. In my view, lighting load and similar low load-factor loads should be penalized very much more heavily than they are at present, and the additional revenue obtained from so doing should be devoted to the further encouragement of the consumer who uses water heating, etc., during the major portion of the 24 hours.

The author does not seem to realize the great difficulty which the supply engineer experiences in framing his tariffs, and the still greater difficulty which often exists in explaining the reasons for the varying tariffs to the consumer. To obtain progressive load conditions, we have to offer to every consumer the lowest possible tariff applicable to the conditions under which he takes his supply. In the electric supply industry we suffer from two handicaps: one is that we cannot store our product, it has to be produced and handed out immediately; and the other is that we have to sell our product before we have bought it. Consequently, in framing our tariffs, we must take in advance a fairly wide view of the possible cost of production or purchase under the grid tariff.

The author stresses the fact that the thing that matters is the actual value of the unit to the consumer for the various purposes to which he puts it. Electric lighting has a high value factor, while electric cooking and heating have not such a high value factor because of the existence of attractive alternative methods of carrying out these processes. It is for precisely these reasons that the various tariffs are framed as they are; but it is not possible to work to too close mathematical limits in price because of the large number of variable factors which exist in the cost of production and distribution of electricity used for different purposes and at different times.

Dealing with the industrial tariff, I am rather surprised to find the author putting forward as an original suggestion the idea that the maximum demand should only be charged if that demand is experienced during a certain specific time. Tariffs based on this principle have, of course, been in operation in the electric supply industry for many years. I think that any attempt at load limitation or restricted-hour periods for the use of electricity for domestic purposes is doomed to failure, and will be very bad publicity for the industry, as the average housewife will find the cutting-off or the limitation of supply at specific times of the day most objectionable and inconvenient. Industrial concerns are in rather a different position, as they work definite hours and their processes can usually be adjusted to suit the restricted-hour tariff.

Mr. L. C. Grant: I rather disagree with one speaker who seems to regard the paper as an attack upon the supply engineers. The only justification for this that I can see is where the author says that in certain quarters the engineer has a habit of passing on the grid tariff to the consumer, either without modification or with an addition of about 10 per cent. With the author's criticism I entirely agree. No account and no advantage is taken of diversity. I find that any attempt to pass on the grid tariff in its usual form and magnitude to industrial consumers of any size frequently produces irritation, and if there is no option but to put forward the grid form of tariff it must be done in a tactful way. But the engineer should realize that diversity is of assistance to him and should be to his consumers also.

I think it is correct to say that such tariffs were designed primarily for the supply authority and for the supply authority's conditions. They are applicable to certain types of industrial load beside the supply authority —such, for example, as a mixed industrial load. One such consumer frequently takes 10 million units annually, and can claim a low average unit cost. When the Central Electricity Board commenced operations, coal cost much less than it does now, and generating plant was of lower efficiency. To-day it is possible to buy small plant with an efficiency as high as that of the plant which the Board originally visualized 15 years ago and upon which they based their tariffs. For example, development work in the last 5 years has produced turbines of 5 000 and 10 000 kW capacity with an efficiency as high as that attained by machines 10 times their size 15 years ago.

Only rarely in the last 10 years or so have I advised clients to install generating plant, but during the last 12 months the position has become less clearly defined. The Central Electricity Board should be in a position to compete, and I think they can do so. Nevertheless, difficulties frequently arise which I consider are more often than not due to the fact that the two-part tariff does not meet the conditions: or is it that large-plant efficiencies are not what they should be, or that the capital cost is high?

The author rather leads us to believe that he is going to tell us about some new method of working two-part tariffs. All that he has done, however, is to put into words what most supply authorities are already doing—Liverpool, for example, is selling during the ordinary peak hours of 4 p.m.–6 p.m. at a fixed price per kW. What is implied here is perhaps that a tariff of this type can be used to improve conditions, not so much by putting in distant control apparatus as by shifting the demand to other peak hours, a job which to me appears to be perfectly well taken care of by the ordinary motor-driven time switch.

I notice several references to French literature, mostly based upon work that was done in Switzerland a few years ago. What was done then was to restrict the load during peak hours so as to get the demand spread over the 24 hours, and this was controlled automatically from the station so as to improve the load factor. By this means the load factor was raised from 30 per cent to something like 80 per cent. There are many references to this work in the *Revue Générale de l'Électricité*.

There are a great many loads which cannot be taken care of by a two-part tariff. Take, as an example, a modern bakery: at one of these two electric ovens are installed, each of which consumes 2 million units a year, and another oven is being installed which will consume 5 million units a year. In the first case it was pointed out to the supplier that it was impossible to run this oven commercially on a two-part tariff, and as a result a special tariff was constructed, equally profitable to the consumer and to the authority.

Mr. G. Lloyd Williams: On page 329 the author rather belittles the value of electricity, but he also calls it "an 'inestimable' boon." I think that the "'inestimable' boon" of electricity is of a permanent character, and not something that disappears immediately the consumer is connected. Electricity is not used because it is cheaper than available alternatives; on the contrary, it is almost invariably the dearest form of energy. To prove this we have only to consider the tariffs offered by electricity's nearest competitor, the gas industry; for industrial purposes the gas industry offers what is equivalent, taking into account combustion efficiency, to a flat-rate unrestricted tariff of 0·2d. per unit. The demands of industry are by no means limited to lighting and motive power; for instance, under the recent Factories Act, factory owners are obliged to provide adequate space heating wherever persons are continuously employed. Heating to the required temperature of 60° F. can be achieved by combustion of solid fuel or gas, or, at a somewhat higher running cost, by electrical means; if the latter course is adopted the sole deciding factor will be the "inestimable boon" or monetarily inassessable advantages of electrification. It is also apparent that competition in the industrial field is not, as the author suggests, confined to private generating plant.

The present tariff situation is attributable to the fact that the major proportion of electricity supply costs bears no relation to units output, or to what Mr. Bolton has defined in one of his books as the "high degree of capitalization of the electricity supply industry." I suggest that this high degree of capitalization is merely a temporary state of affairs. The "fixed" portion of supply costs are to a considerable extent a function of the rate of increase of connected load, and when a more stable condition is attained very much lower tariffs will automatically become possible. At the present time plant rapidly becomes obsolete for the sole reason that it is inadequate to cope with the increased demand.

When considering the peak load, it must be borne in mind that the peak period occurs simply because consumers require electricity mostly at this time, and this should not be lost sight of when considering restrictions and charges relative to the peak. The author suggests that superimposed control be employed either for changing metering arrangements so as to bring an increased tariff into operation during the peak or for cutting off unnecessary load. I think that it is very difficult to decide what constitutes unnecessary load, particularly in the case of domestic consumers. Perhaps the author could be more explicit on this point. In general, I do not see that it is practicable to cut off any load other than that which has a relatively high storage capacity on the consumer's premises; that is, cutting off supply should not interrupt the service to the consumer. Increasing the tariff during the peak period is the more satisfactory alternative, but from experience of consumers I have found that it is desirable that the increase in charge should be kept as low as possible, even should this mean increasing the off-peak charge.

The author appears to regard the domestic non-lighting load as an unavoidable evil which is readily open to restriction; I do not agree with him. A short time ago I had the opportunity of examining some analysed load curves for a fairly representative medium-size undertaking, and I was interested to note that the domestic load was in general tending to move in opposition to the total system load, and at the main system peak tended to maintain the demand, and to prevent what would otherwise have been a sudden collapse of load.

It is not surprising that the Hopkinson tariff has not "swept the board" in the domestic field, as it is not at all applicable in this direction. It is customary to find that an average domestic consumer, employing cooking and lighting, has an individual load factor as low as 2 per cent, but when a group of such consumers is considered the overall result is quite satisfactory, as owing to the high diversity of use an overall load factor as high as 40 per cent may be realized.

The domestic storage cooker is mentioned as being very desirable from the point of view of load levelling. It would appear that this type of cooker, with a low constant load and a higher hob boosting load, would effect a substantial increase in individual consumers' load factors; but as cooking—at least, a large part of domestic cooking—is carried out during the peak period, and it is only to be expected that the majority of the booster elements would be on at this time, the overall result would differ little from the present position. I should, however, like to know the author's opinion as to why this type of cooker, introduced some time ago, has not become popular.

THE AUTHOR'S REPLY TO THE DISCUSSIONS

Mr. D. J. Bolton (*in reply*): I quite agree with the view of Mr. Kennedy and Mr. Melling that incremental cost must include a share in all capital charges (dependent on the extent of peak incidence), since, as Mr. Kennedy says, a time comes when the cables are loaded up and one has to lay out additional capital to supply further units. Actually, capital expenditure takes place in jerks, but a tariff must average these jerks: in the long run, extra units at normal hours mean extra plant, and every unit must bear its share. Hence the incremental cost may not be much less than the average cost for the same load-factor conditions. But this argument destroys Mr. Kennedy's later statement that once a system has been laid out a deduction of 1 kW of demand on peak load only saves £2 10s. to £3. It is precisely because a system is not static, but must be continually expanded to meet added demand, that a reduction of 1 kW will in the aggregate save the larger amount that I have suggested.

Mr. Kennedy says that most suppliers have had to depart from the Hopkinson tariff and charge a slightly higher amount per month, and he asks whether I propose that consumers should pay a very high fixed charge for demand during certain hours only. My suggestion is intermediate between these two extremes. I propose a block tariff as at present, but rather lower, so that it carries some but not all of the fixed costs. The remainder can be covered by a (relatively small) fixed charge levied only during peak hours. I should further emphasize that my suggestion of superimposed control for industrial loads was not to interrupt the supply but merely to operate the demand mechanism. The principle that Mr. Kennedy describes as "logical" for transmission costs, namely charging for demand irrespective of the time when it occurs, means charging our clients according to what it would cost them, not according to what it does cost us. It is a well-recognized commercial principle, but do not let us delude ourselves into thinking that it is a costs tariff. It is a use-value tariff, pure and simple.

Mr. Sumner, Mr. Pryce-Jones, and Mr. Grant point out that a time-of-day kilowatt charge in an industrial tariff is no novelty, and I regret this implication in my paper. What I meant to suggest was that the *method* of operating the demand metering (by superimposed control) was, I believed, novel and untried. (In this connection I accept Mr. Bernard's criticism that my paper does not sufficiently emphasize the merit of flexibility of superimposed control methods in the face of shifting peak times.) The hypothetical example Mr. Sumner mentions is one of the hard cases that make bad law. Clearly, any off-peak endeavours should be directed towards consumers whose loads are small in comparison with the total load. It would be absurd to apply them to a consumer whose load represented half the total undertaking.

Prof. Kapp fears that if the kilowatt charge is removed for certain parts of the day it will have to be greater at other times in order to bring in the same revenue. This is true, but in a great many cases the Hopkinson tariff has already been abrogated and its place taken by a use-value tariff of the block-rate type. I suggest that this goes too far in the other (non-cost) direction, and that it should be combined with a time-of-day kilowatt charge of moderate size as explained in the reply to Mr. Kennedy.

The example quoted by Messrs. Hallowell and Osborne is of very great interest. I quite agree with the latter that one great advantage of superimposed control is the power it gives an undertaking of switching off non-essential loads and therefore in effect "switching on" spare plant capacity. I still maintain, however, that there are other loads in which an interruption of supply would be disastrous but where switching on a tariff charge would be both practical and salutary. Superimposed control can be used either to avoid the peak or to pay for it.

Mr. Rowson makes a suggestion for investigation which in my opinion would yield valuable results and well repay its cost. It is extraordinary how little research has been done in the utilization field. Some of the water-heater difficulties he mentions, including the sudden rise in load on restoration of supply, can be met by some form of discriminatory switching such as that described by Messrs. Hallowell and Osborne, and referred to by Mr. Melling. In criticizing my notes on diversity Mr. Rowson omits my qualifying words. I suggest that *for users within a given band of working hours* a large number of low load-factor consumers are *nearly* as good as a smaller number of high load-factor consumers—sufficiently nearly, at least, to make the Hopkinson tariff substantially irrelevant.

Mr. Pryce-Jones considers that any attempt at load limitation for domestic purposes is doomed to failure. But in the very popular storage heater the domestic user is already subject to a load limitation, since once the hot contents are exhausted considerable time is required for recovery. A somewhat larger-capacity heater, coupled with a limited supply interruption, would give the domestic user precisely the same hot-water service as he now obtains from his smaller heater with continual supply. Both Mr. Pryce-Jones and Mr. Lloyd Williams stress the difficulties which may arise from interruption of supply. I would certainly only suggest intermittent supplies for specific loads and with consuming apparatus expressly designed for the purpose. Mr. Lloyd Williams gives an interesting example of the inverse relationship between load and diversity factors mentioned in my paper and referred to by Mr. Rowson in the London discussion.

OPERATING EXPERIENCE WITH HIGH-VOLTAGE ALTERNATORS

By W. D. HORSLEY, Member.*

[*Paper first received* 3*rd June, and in revised form* 12*th October*, 1939; *read before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 11*th December*, 1939, *and also before the* NORTH-EASTERN CENTRE 22*nd January*, *before the* TEES-SIDE SUB-CENTRE 7*th February*, *before the* NORTH MIDLAND CENTRE 17*th February*, *and before the* NORTH-WESTERN CENTRE 19*th March*, 1940. *The paper would also have been read and discussed before* THE INSTITUTION *on the* 7*th December*, 1939, *but the meeting was cancelled owing to the war*.]

SUMMARY

The paper reviews experience with high-voltage generation since the first high-voltage concentric-conductor alternator was commissioned in August, 1928. This generator has given trouble-free service for a period of over 11 years. Since then 20 alternators of this type have been placed in commission, and another 13 are under construction.

The operation and reliability of these alternators has been in general satisfactory and has justified the adoption of high-voltage generation.

An account is given of the few difficulties experienced and of the steps taken to overcome them.

A brief description is given of the development of a new technique in the construction and manufacture of high-voltage concentric-conductor alternators and also of a new "vacuum pressure" impregnating plant capable of accommodating stators of over 130 tons in weight.

The protection of high-voltage generators and the effect of direct generation on system operation are also discussed.

INTRODUCTION

Over 11 years have elapsed since the first 33-kV high-voltage concentric-conductor turbo-type alternator was put into commission in the Brimsdown power station of the North Metropolitan Electric Supply Co. (later the North Metropolitan Power Station Co., Ltd.). The earlier history of this alternator and its successful operation has been fully described in previous papers.[1, 2, 3] The alternator has been in continuous service since it was installed and has given entire satisfaction. The maintenance has been negligible, and the availability of the set during its life has been practically 100 % as far as the alternator is concerned. The conditions of operation have been more severe than average, particularly during the early life of the machine.

There has been considerable development in high-voltage alternator construction during the last decade, and there are now 34 concentric-conductor high-voltage alternators running or under construction, amounting to an aggregate of 1 400 000 kVA. The number of concentric-conductor alternators in commission is 21, and up to the present time the total "machine years" of service is 69. Out of a total of 21 in service, 4 machines have been subject to difficulty; the remainder have given trouble-free service and complete reliability.

A list of high-voltage alternators of the concentric-conductor type in service and in course of manufacture is given in the Table. The output of concentric-conductor alternators in service and under construction is shown by the curves in Fig. 1.

A review of the difficulties experienced is given in Parts 1 and 2 of the paper, and in Part 3 problems which affect the operation of the system are discussed.

PART 1

HISTORICAL REVIEW OF EXPERIENCES WITH HIGH-VOLTAGE CONCENTRIC-CONDUCTOR ALTERNATORS

The account of the failures, whether due to weakness in the machine or to external causes, is given as far as possible in chronological order.

(1) 25 000-kW 33-kV Alternator commissioned in the Brimsdown Power Station in May, 1932 (Second machine)

(*a*) A failure of the slot insulating tube between an outer conductor and the core occurred after 55 hours in service. The alternator was tripped off the busbars by the protective apparatus, and the damage was slight. The bar was replaced in a few days,[5] and this experience served to demonstrate the rapidity with which a bar can be replaced in the concentric type of winding. An examination of the faulty bar indicated that there may have been a flaw in the insulation at the point of failure, but any definite evidence had been destroyed by the arc.

A second breakdown of the same kind and due to the same cause occurred in May, 1938. Soon after this machine had been manufactured improved methods of inspection and testing, including the measurement of the dielectric losses of individual bars, were introduced, and the possibility of a faulty conductor being fitted in an alternator manufactured after that time is very remote.

(*b*) In November, 1933, a flashover took place from the end windings of the alternator to the stator frame, and simultaneously a flashover to earth occurred from one terminal on the main oil circuit-breaker controlling the alternator. A careful examination showed that the path of the flashover in the stator windings passed through at least 4 in. of air, and it was evident that it could have been caused only by an extremely high over-potential, exceeding 70 kV. The normal operating potential of the winding to earth at the point of the fault was 6·5 kV. At the moment when the flashover occurred the alternator was isolated from the system and had just been excited to normal voltage prior to being synchronized with the main busbars.

The investigations which followed revealed that the primary winding of the voltage transformers which are connected to the machine side of the switch had an earthed neutral point. In this respect the second high-voltage alternator installed at Brimsdown differs from the first, which has a voltage transformer with an insulated primary winding. The diagram of connections for both alternators is shown in Fig. 2.

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* Messrs. C. A. Parsons and Co., Ltd.

Table

LIST OF TURBO-ALTERNATORS OF THE CONCENTRIC-CONDUCTOR TYPE, IN SERVICE OR ON ORDER, DESIGNED TO GENERATE AT 33/36 kV, UNLESS OTHERWISE STATED

Name of purchaser	Destination	Speed	Rating	Date of commission
		r.p.m.	kVA	
Council of the City of Cape Town	Table Bay	3 000	62 500	30.1.39
Council of the City of Cape Town	Table Bay	3 000	62 500	24.3.39
Council of the City of Cape Town	Table Bay	3 000	62 500	16.8.39
Glasgow Corporation (20 kV)	Dalmarnock	1 500	62 500	3.11.37
Glasgow Corporation (20 kV)	Dalmarnock	1 500	62 500	30.9.38
Birmingham Corporation	Hams Hall " B "	1 500	62 500	—
Birmingham Corporation	Hams Hall " B "	1 500	62 500	—
Electricity Supply Commission, S. Africa ..	Congella	3 000	47 100	—
Victorian Railways Commissioners (20 kV) ..	Newport " A "	1 500	39 500	—
County Borough of Swansea	Tir John	3 000	37 500	27.8.35
County Borough of Swansea	Tir John	3 000	37 500	30.9.35
Northampton Electric Light and Power Co. ..	Hardingstone	3 000	37 500	29.4.36
Northampton Electric Light and Power Co. ..	Hardingstone	3 000	37 500	—
Kingston-upon-Hull Corporation (22 kV)	Sculcoates Lane	3 000	37 500	29.10.37
Electricity Supply Commission, S. Africa ..	Congella	3 000	37 500	6.10.38
City of Leicester	Freemen's Meadow	3 000	37 500	—
County Borough of Derby	Full St., Derby	3 000	37 500	—
South Wales Electric Power Distribution Co.* ..	Pontypridd	3 000	37 500	Sept., 1939
South Wales Electric Power Distribution Co.* ..	Pontypridd	3 000	37 500	—
Corporation of Dundee*	Caroline Port	3 000	35 625	—
North Metropolitan Power Station Co.* ..	Willesden	3 000	35 294	—
Calcutta Electric Supply Corporation	Mulajore	3 000	35 294	Oct., 1939
Calcutta Electric Supply Corporation	Mulajore	3 000	35 294	—
Calcutta Electric Supply Corporation	Mulajore	3 000	35 294	—
North Metropolitan Power Station Co.	Brimsdown	3 000	31 250	16.8.28
North Metropolitan Power Station Co.	Brimsdown	3 000	31 250	25.5.32
South Wales Electric Power Distribution Co. ..	Pontypridd	1 500	31 250	16.10.36
City Electric Light Co.	Brisbane	3 000	31 250	—
East Rand Proprietary Mines (22 kV)	S. Africa	1 500	26 666	14.2.35
East Rand Proprietary Mines (22 kV)	S. Africa	1 500	26 666	5.5.37
Electricity Supply Commission, S. Africa ..	Salt River	3 000	25 000	29.6.33
Electricity Supply Commission, S. Africa ..	Salt River	3 000	25 000	24.6.34
Electricity Supply Commission, S. Africa ..	Salt River	3 000	25 000	17.5.35
South Wales Electric Power Distribution Co. ..	Pontypridd	1 500	24 000	30.10.34

* Manufactured under licence by The English Electric Co., Ltd., Stafford.

An examination of the characteristics of the voltage transformers and of the capacitance of the alternator windings and connecting cables showed that the conditions which gave rise to the phenomenon known as neutral inversion or neutral instability were present. It was calculated that the potential of the windings, cables, and switchgear could build up to 75–100 kV, which agreed closely with the value deduced from the examination of the failure.

Several methods of preventing neutral inversion are considered and discussed in Part 2 of the paper.

It was impracticable to isolate the star point of the voltage transformers as they are single-phase units housed in separate tanks and forming part of the main circuit-breaker panel, which is of the metalclad phase-isolated type. In this type of switchgear the neutral end of the primary winding of each unit is connected internally to the earthed enclosure. It would be possible to bring out an insulated connection to a neutral point only by fitting an expensive high-voltage bushing in each transformer chamber.

It was eventually decided to earth the neutral point of the alternator. No provision had previously been made for earthing the neutral points of either alternator, as the system was earthed at another point. It was necessary at this time to adhere to this arrangement and to earth the alternator only when running excited disconnected from the system.

The alternator neutral is automatically disconnected when the alternator is synchronized with the system and automatically reconnected when the alternator is taken off the busbars. Should the alternator be tripped out by the protective gear the alternator neutral point is not earthed and the field is suppressed by the opening of an automatic field-breaking switch. With this arrangement neutral inversion can occur only during the brief period in which the alternator is running excited after it has been disconnected from the system by the protective gear.

In November, 1938, the alternator under discussion was tripped off the busbars by the protective apparatus simultaneously with an 11-kV generator coupled to the system through a step-up transformer: it was found that a breakdown of the transformer had occurred. The high-voltage alternator was excited and again connected to the system. About a fortnight later this alternator was again tripped off the system by the protective gear, and an examination showed that a flashover had occurred between an end connection and the stator core along the outer surface of the conductor insulation. The amount of burning on the core and conductor was small, and the damage to the insulation superficial. The length of the path of the flashover was over 7 in., which, in conjunction with the appearance of the fault, indicated that it had been caused by overvoltage.

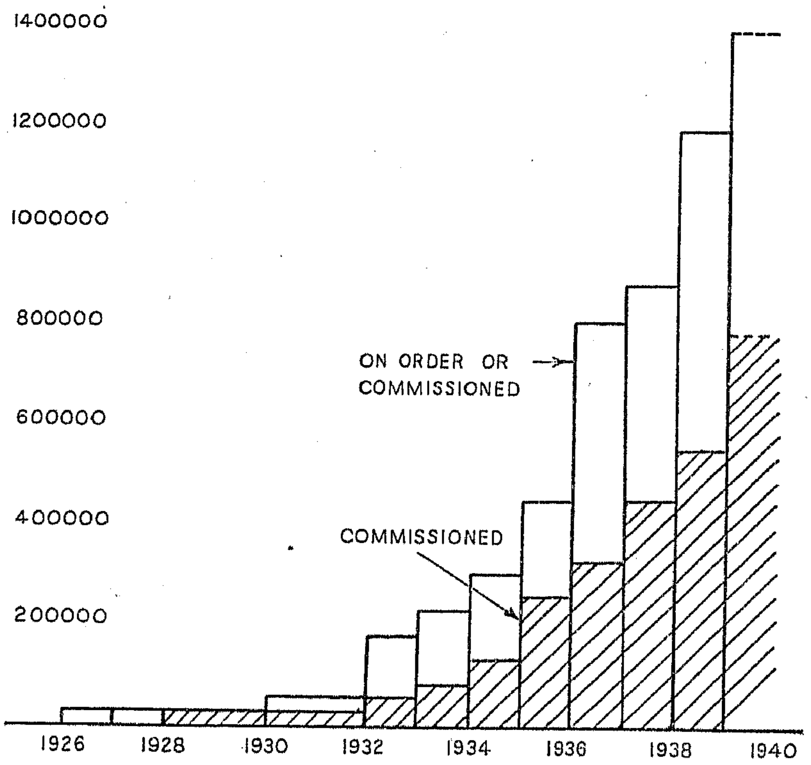

Fig. 1.—Increase in output (in kVA) of concentric-conductor type of high-voltage alternators.

In order to prevent neutral instability under any conditions additional precautions were considered. Various methods of dealing with this problem are discussed later in the paper.

(2) 20 000-kW 33-kV Alternators—Salt River Power Station, Cape Town

After the experience with neutral inversion at the Brimsdown power station, precautions were taken to avoid a repetition on other high-voltage alternators having voltage transformers with the neutral point of the primary winding earthed.

At Salt River the 33-kV network, to which three high-voltage generators are connected, is earthed at the neutral point of one or more transformers interconnecting the 33-kV and 12-kV systems. The alternator neutrals are insulated during normal operation and the neutral points of the voltage transformers are earthed. Initially, the precaution was taken of earthing the alternator neutrals whenever they were running excited and disconnected from the busbars, but later it was considered unlikely that instability would occur, and this practice was discontinued. The earthing equipment was therefore removed and the alternator neutrals left isolated under all conditions.

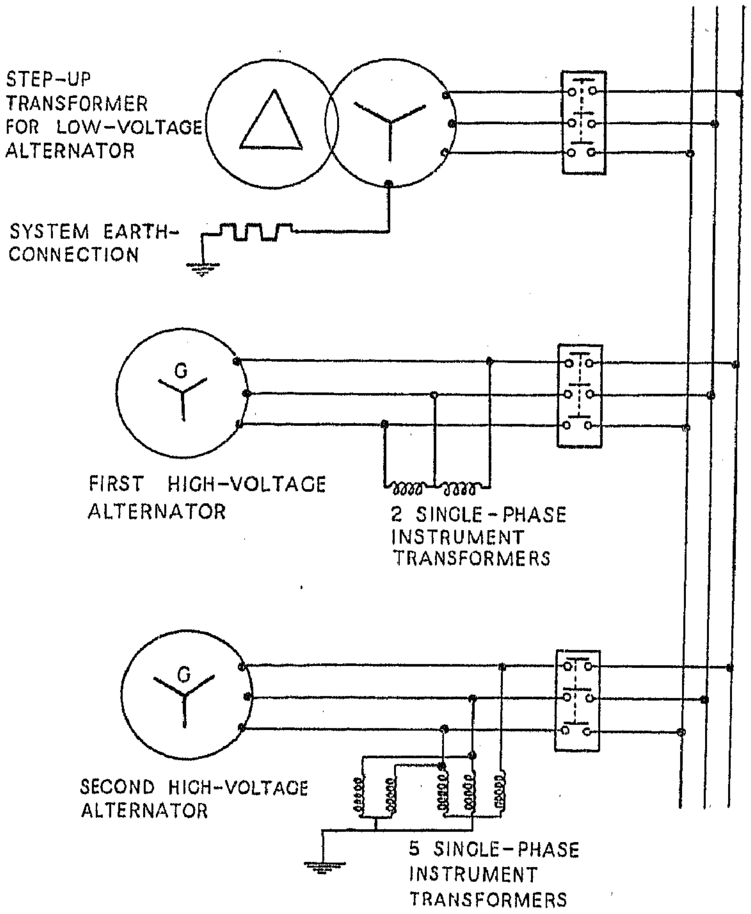
STEP-UP TRANSFORMER FOR LOW-VOLTAGE ALTERNATOR
SYSTEM EARTH-CONNECTION
G
FIRST HIGH-VOLTAGE ALTERNATOR
2 SINGLE-PHASE INSTRUMENT TRANSFORMERS
G
SECOND HIGH-VOLTAGE ALTERNATOR
5 SINGLE-PHASE INSTRUMENT TRANSFORMERS

Fig. 2.—Schematic diagram of 33-kV connections.

In 1937, flashovers occurred across the bare lead extensions of two of the alternators, and since the leads were located in the alternator air circuit the fault extended to the end windings and caused much damage. As the failures occurred on load the cause was not at first obvious. The first stator was returned to England for a complete investigation, but no evidence of weakness was found in the windings. The damaged windings were removed and the remainder withstood a graded pressure test of 60 kV. When the second failure occurred, a short time after the first, a further examination was made on site and an important discovery was made on the third set, which was still in satisfactory operation. Small arc-craters, which were unmistakably caused by flashovers, were found in the metal bases of the insulators supporting the lead extensions. It was necessary to put the set back into service immediately, and after it had been running a week a further inspection was made. New signs of arcing were discovered, confirming the existence of high over-voltages. The normal 50-cycle flashover value of the insulators when new was 135–140 kV, but further investigations and experiments showed that owing to a slight deposit of salt on the surface of the porcelain the flashover value had fallen to 65 kV.

It was found that owing to leakage in the air circuit the salt-laden atmosphere of the Salt River area had penetrated into the air ducts. Moisture also was present, caused by condensation on the air-cooler tubes.

It would be expected that in these circumstances immediately a flashover occurred with the machine excited a power arc would follow, causing much greater damage than the pitting of the insulator supports. The only explanation which seems to fit the facts is that neutral instability occurred when the alternators were de-excited after coming off the busbars, causing a high voltage between the windings and earth. Neutral inversion would be likely to develop with a change in voltage, and as the alternator field died away the duration of a sustained arc would be limited to a short period.

A re-examination of the circuit constants showed that under some conditions there was a possibility that neutral instability might occur and that over-potentials of the order of 100 kV might be anticipated.

The practice of earthing the alternator neutral while disconnected from the bars was reinstated, and the voltage transformers were loaded with a resistance burden connected across the open delta secondary winding of an auxiliary transformer. In addition, lead extension insulators of improved design were fitted and the leads insulated throughout their full length.

The alternators were placed in service again in January and February, 1938, and no further difficulties have been experienced.

(3) 30 000-kW 33-kV Alternators—Tir John Power Station, Swansea

Two 33-kV alternators are installed in the above station; and in March, 1938, a breakdown occurred in the end windings of one of these machines. The alternator was operating on open circuit excited to normal voltage at the time, and was tripped out by the differential protective gear.

An investigation revealed that the fault had originated between the outer and inner sections of a phase along the surface of a conductor between joints. Fig. 3 shows the joint construction and insulation and the path of the fault.

The position of the fault in relation to the winding is shown diagrammatically in Fig. 4. The details of the concentric-conductor winding have already been described in previous papers.[1, 2, 3]

The operating voltage between sections at the position of the breakdown is 6·5 kV, and the insulation is more than ample to withstand this potential. It was appreciated in the course of the development of the concentric-conductor alternator that the insulation of the joints was a vital factor in the construction of the winding, and particular care was taken to obtain the best design and construction. There was no reason to fear a failure, as tests and experiments coupled with the satisfactory performance of the first concentric-conductor alternator for 11 years have proved the joint construction to be inherently sound.

There was no evidence of a high-voltage discharge, and neutral inversion could not take place as the windings of the voltage transformer are connected between phases and are insulated from earth.

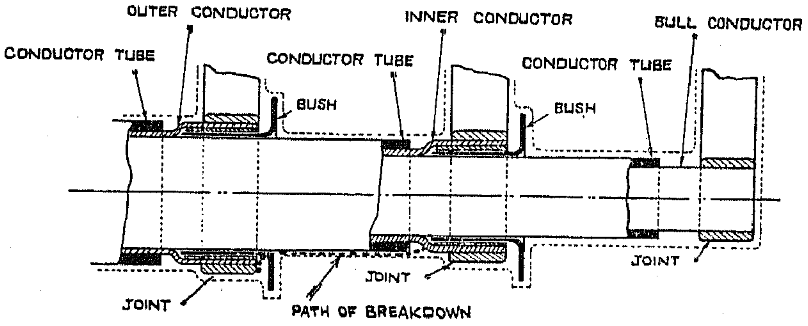

Fig. 3.—High-voltage stator end-winding joint.

An examination of the stator windings showed that there was an inherent defect in the manufacture of the bushes (Fig. 3). These bushes were built up of mica and pressed in a mould. The cylindrical portion was formed from a micanite sheet, the edge being cut in an axial direction at one end so as to form projections, which were turned at right angles and interleaved with micanite washers to form the flange of the bush. The cuts in the tube were staggered so as to avoid a continuous leakage path through the corner of the flange. The bushes, after being formed in this manner, were placed in a mould built up of three external segments and an internal mandril. The outer segments were pressed into position by means of a tapered ring.

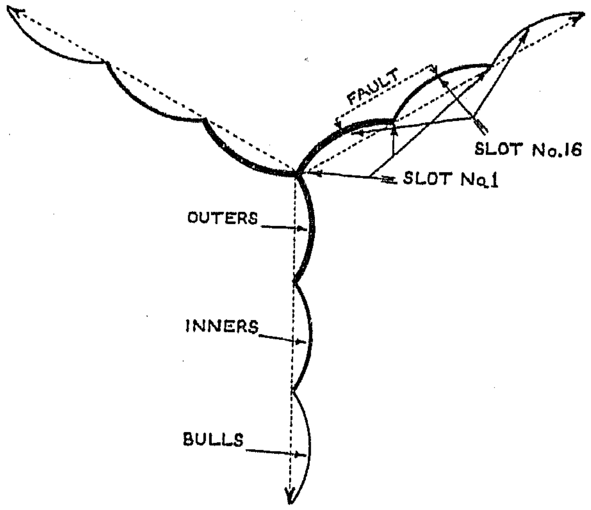

Fig. 4.—Diagram illustrating position of fault.

With this arrangement great care was required in manufacture in order to ensure that the segments fitted accurately when the mould was placed in the press. It was found that in a number of bushes made for the Swansea machine, an excess of material in the cylindrical portion of the bush had been squeezed out into the joints between the segments of the mould. These bushes should normally have been rejected, but owing to a misunderstanding the ridges formed in this way were cut off in order to fit the bushes into the joint.

The removal of a ridge which was in the form of a fold in the wall of the micanite tube resulted in a large reduction in the insulation thickness. An examination of the bushes removed from the machine showed that a few had split along the line of weakness. In addition to destroying the insulating value of the bush the space formed by the crack permitted local ionization and thus initiated a failure by tracking. In view of this discovery it was considered advisable to take the precaution of renewing all the insulating bushes between the joints at both ends of the winding.

As soon as this work was complete and the machine again in commission an examination was made of the second alternator. The insulation resistance between the three sections and from the outer section to earth was measured. It was found that the insulation resistance between the outer and inner sections of the phase corresponding to the one which had failed in the first alternator was low. A pressure of 17 kV, nearly 3 times the working pressure, was applied, resulting in the breaking-down of a few conductors between the inner and outer joints. These conductors were replaced, and the insulation resistance then increased to the same value as that of the corresponding sections of the other two phases.

It was clear from the investigations that it was more than a coincidence that the same phase at the same end was affected in two machines. While the major cause of the failure was undoubtedly a faulty bush, other contributory factors were found. The most important of these was a shortage of ventilating air, resulting in uneven cooling of the end windings at one end of the alternator. The location of the affected joints at the same place in both machines was thus explained. The cooling of the windings was readily improved by installing larger ventilating-fan units.

It was also found that the temperature level was generally high, owing to running the machine with only one fan in operation at the higher loads.

Another feature peculiar to these alternators was the unusually high pressure tests—40 kV applied between each conductor and 50 kV between the outer conductor and earth. These tests are equivalent to applying 130 kV between the bull conductors and earth. While the insulation thickness and, in the complete winding, the leakage surface between joints, are ample to withstand this voltage, the test had to be applied with temporary insulation on the ends before the conductors were inserted in the stator core.

An inspection of the conductors in the stator and of the spare bars indicated that the discharge which had taken place during the test had caused slight deterioration of the insulation surface, which may later have led to tracking. The voltage usually applied between conductors during construction is 34 kV, which is nearly 5½ times the normal working voltage.

A few other minor factors were found in the investigation, which, while not important in themselves, have been of value in pointing the way to improvements in construction and manufacture.

PART 2

PRACTICAL DIFFICULTIES, AND THE STEPS TAKEN TO OVERCOME THEM

The difficulties which have been reviewed historically in Part 1 may be grouped as follows:—(1) Conductor insulation. (2) Joint insulation. (3) Over-potential caused by neutral inversion.

The steps which have been taken to overcome these difficulties are described below.

(1) Conductor Insulation

The failure of the insulation of a conductor to earth has occurred in only one alternator. It was found that the outer insulating tubes in this machine were of slightly less than the designed thickness, and that, in addition, there may have been a flaw at the point of breakdown. The thickness of insulation normally provided between conductors and to earth is ample to withstand the voltage stresses occurring in service under both normal and fault conditions. This type of breakdown is not peculiar to the high-voltage concentric-conductor alternator conductor, and may be experienced with any form of electrical apparatus.

Since the alternator under discussion was built considerable improvement has been made in the testing of conductors during manufacture. In addition to the making of pressure tests during construction, the dielectric losses of every conductor are measured; any conductor with a high loss is re-impregnated and, failing a satisfactory improvement, is rejected.

The conductors are carefully inspected and gauged at every stage of manufacture, while the manufacturing process itself, and particularly the drying-out and impregnating operations, are rigorously checked by a technical expert with the aid of a complete set of recording and indicating instruments. Amongst later improvements a new impregnating plant for conductors has been installed (Fig. 5, see Plate, facing page 352). With this equipment the pressure may be reduced to 2 or 3 mm. of mercury, and a pressure of 60 lb. per sq. in. is later applied with the bars immersed in varnish. Many new features also have been incorporated, and the drying and impregnation cycle modified and improved in many respects.

The quality of the insulation has been greatly improved by the new process. The breakdown strength and the limit of stability have been appreciably increased.

Improvements have also been effected in the making of micanite sheets with which the conductor insulation is built up. An instrument which measures the thickness of the sheet at any point has been devised, and every sheet is examined visually on a ground-glass table uniformly illuminated from below.

The possibility of a faulty bar being fitted in an alternator is now practically eliminated.

(2) Joint Insulation

While the satisfactory operating experience with the concentric-conductor winding proves the construction to be sound, investigations following the failure of a joint showed that a number of improvements were possible.

It was evident that it was necessary, firstly, to modify the construction of the insulating bush, which is an important part of the joint insulation; and secondly, to secure the complete elimination of spaces or voids in the construction of the joints.

The manufacture of the bush was considered carefully, and it was decided that the method which has been in satisfactory use for commutator V rings for many years would give the most reliable product. In the new construction the bushes are built up of several layers of overlapping strips of micanite. The strips are first punched out of sheets of pressed micanite to the shape shown in Fig. 6. The straight part of the strip forms the cylindrical portion of the bush, and the segmental part the flange. First, the strips are heated and placed in a mould which bends the segmental portion at right angles and at the same time forms the correct radius of curvature in the straight portion. The formed segments are then assembled carefully by hand in layers on a mandril and each strip is held in place by varnishing and heating with a hot moulding iron. The loosely assembled bush is placed in a mould of new design, which was evolved only after a considerable amount of thought and investigation. The bush is pressed in the mould at a high temperature and pressure for some hours. After removal from the mould the edge of the flange and the ends of the bush are trimmed to the correct size and shape by turning with a diamond tool. The finished product is uniform in thickness and within a thousandth of an inch of the correct dimensions. Finally, the bush is inspected and pressure-tested to 25 kV for 1 minute before being fitted into the alternator.

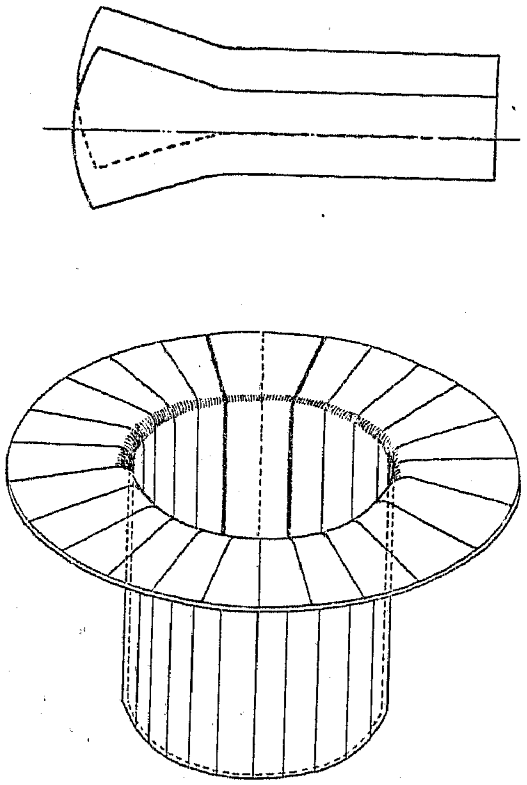
Fig. 6.—Construction of micanite insulating bush.

The general form of construction of the joints was determined only after some years of investigation and experiment, and has not been changed; but a number of modifications have been made in detail. A more uniform voltage-gradient in the joint insulation has been obtained by radiusing the end connection eyes. Air spaces have been eliminated by carefully filling in the gaps between the conductor strands with an insulating compound.

A new technique also has been developed for the making and insulating of the joints. In the new process the stator is supported in a vertical position on steel trestles, and after a bank of end connections has been fitted on top the stator is turned on trunnions and the joints sweated on the under-side. The joints are heated electrically for this purpose. Any excess solder which runs out of the joints falls clear of the windings. The assembling of further banks of end connections, the fitting of bushes and the insulating of joints which have already been sweated, are carried out on top.

Amongst other improvements in details of the insulation of the joints and connections, is the use of glass silk as an insulating material. It is also being used in place of cotton or silk for other purposes. Glass silk has the advantage that it is an inorganic and inert substance. It is more durable and will withstand a higher temperature than cotton or silk; the individual fibres, being solid, cannot absorb moisture.

The practice of drying and impregnating conductors, coils, and small machines under vacuum and pressure is almost universal. The advantage of thoroughly impregnating completed windings with insulating varnish in order to eliminate air spaces is recognized widely, and the only reasons for not applying this treatment to large machines are the high cost of, and large amount of space occupied by, the necessary equipment.

This question was carefully considered by the firm with which the author is associated, and it was decided that the provision of a suitable plant for the vacuum-pressure impregnation of the completed windings of the largest stators was justified.

The equipment was installed and completed in an extension of the main shops early in 1939, and is illustrated in Fig. 7 (see Plate).

The main vacuum-pressure impregnating chamber is a vertical cylindrical tank about 18 ft. in diameter, and it can accommodate stators of an overall length of 26 ft. and weighing over 130 tons. The tank is sunk in a pit in the shop floor. A stator is brought up to the required temperature for drying out by circulating heated air and by passing a current through the windings. During the drying process the pressure in the chamber is reduced to 1 or 2 mm. of mercury by means of a special pump. The impregnating varnish is stored in a heated vessel and admitted when required to an inner tank in the main chamber so as completely to immerse the end windings of the stator. Air is admitted through a silica-gel drier and raised to a pressure of 30 lb. per sq. in. which is maintained for some hours. Provision also is made for breaking the vacuum with carbon dioxide.

After the varnish has been withdrawn the pressure is lowered in order to draw off the solvent from the varnish in the windings. In some circumstances the windings may be impregnated a second time, in order to fill any spaces left after the removal of the solvent.

Then the stator is reversed in position and the sequence of operations repeated on the windings at the other end. After the cycle has been completed, dry heated air is circulated through the tank in order to oxidize the varnish.

(3) Over-potential caused by Neutral Inversion

The danger of a flashover due to an over-potential caused by neutral inversion may be present in any type of electrical apparatus where the conditions are suitable. Neutral instability is a complex form of resonance and is liable to occur where a 3-phase alternator, transformer, or other apparatus with windings and connecting cables of appreciable capacitance to earth, is earthed through the neutral point of an instrument transformer. This phenomenon has been described and analysed in several technical papers, [7, 8, 9, 10, 11] and it is unnecessary to describe it in detail. As far as the author is aware, the phenomenon has been experienced on only three high-voltage alternators, as described earlier in the paper. Two of these machines are installed in the same station and operate under the same conditions.

While there have been a number of instances of neutral inversion on apparatus connected to lower-voltage networks or systems, it appears to have been of less frequent occurrence in comparison with the amount of plant installed. It should not be concluded, however, that the recent experiences with neutral inversion in 33-kV systems are due to the constants of the circuits associated with 33-kV networks or with 33-kV alternators and transformers. The reason is that phase-isolated switchgear provided with voltage transformers having an earthed neutral point is more often selected for 33-kV circuits.

All large 33-kV apparatus may be connected to the system through switchgear of this type. When the switch is open the equipment is isolated and may be earthed only at the neutral point of the transformer. The high impedance of the transformer windings in conjunction with the capacitance to earth of the apparatus and connected cable may form a resonant circuit. The current flowing through the capacitance leads the applied voltage by nearly 90°, while the fundamental magnetizing current of the transformer lags by about the same angle, the total current being the vectorial sum of these two components.

Since at low voltages the magnetizing current is small compared with the capacitive current, the total current at first is leading and varies approximately as the voltage. At some higher voltage the magnetizing current increases more rapidly owing to saturation in the magnetic circuit of the transformer, and an unstable point on the curve is reached above which the total current decreases with increasing voltage; the potential of the line to earth may then increase, without further adjustment of the applied voltage, to many times the normal value. The characteristic current/voltage curve is shown in Fig. 8.

Since the phenomenon may occur successively on each line, the oscillation of potential may be at half, double, or the normal frequency.

Neutral instability may be prevented in several ways, some of which are as follows:—

(i) Isolation of the neutral point of the voltage transformer.

(ii) Earthing of the neutral point of the alternator, either directly or through a comparatively low resistance or reactance.

(iii) Connection of a loading resistance across the secondary winding of the voltage transformer in addition to the normal burden.

(iv) Connection of a damping resistance in the open delta of a tertiary winding provided in the voltage transformer for this purpose.

(v) Connection of a surge arrester between the neutral or terminal points of the alternator and earth.

(vi) Connection of a spark-gap between the alternator neutral-point and earth.

(vii) Connection of a resistor of the ceramic type between the alternator neutral-point and earth.

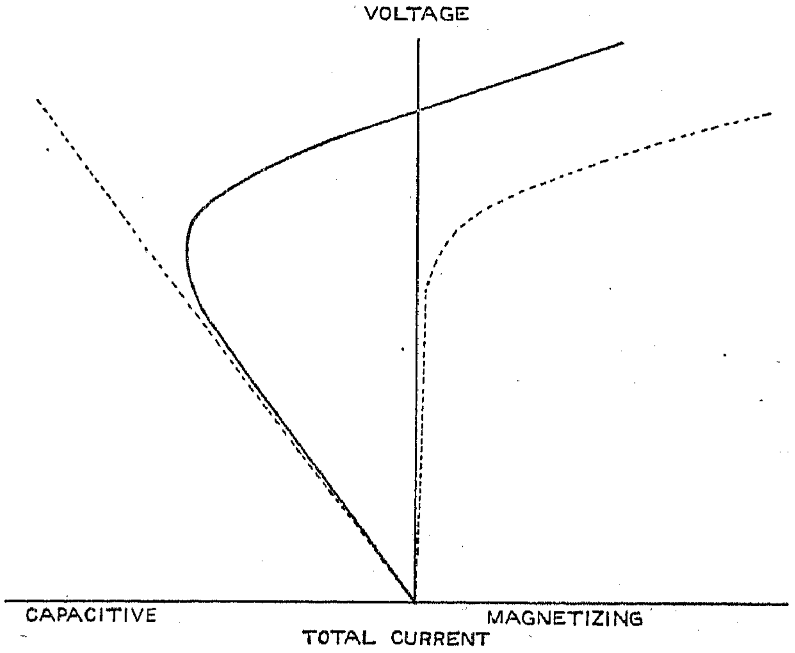

Fig. 8.—Characteristic current/voltage curve for neutral inversion.

(viii) Installation of a voltage transformer designed with a low saturation in the magnetic circuit at normal voltage.

The ideal method of preventing neutral inversion is to isolate the star point of the voltage transformer, but for the reasons already mentioned this course is not always practicable. The earthing of the alternator neutral through a comparatively low value of resistance or reactance is an equally certain solution of the problem.

Calculations and experiments show that a loading resistance across the secondary winding of the voltage transformer is effectual in preventing resonance, but it has the disadvantage that unless a large transformer is installed the additional load may affect the accuracy of the instruments connected to the transformer.

Investigations have shown that a damping resistance connected to the open delta of a tertiary winding would prevent neutral inversion, but the method has not yet been proved in practice. This method has the advantage that it does not affect the accuracy of the meters, and it can be applied to existing equipment by adding an auxiliary transformer with a delta-connected secondary winding.

The limitation of over-potential by means of a surge arrester or a ceramic resistor should be effectual provided that the correct characteristics can be obtained.

Spark-gaps of the sphere and the paper gap type are simple and have been used successfully for both high- and low-voltage alternators.

The provision of a voltage transformer with a low saturation value at the normal operating voltage is not in itself a cure, but it is a precaution which always should be taken and for some years it has been the standard practice of the leading switchgear makers.

(4) Ozone

Many operating engineers have raised the question whether the smell of ozone which is sometimes noticeable in the vicinity of high-voltage alternators is caused by a high-voltage brush discharge in the windings and therefore likely to be harmful.

The generation of ozone is not confined to high-voltage alternators and is common in machines operating at 11 kV and over. While the characteristic smell is usually attributed to ozone it may be largely due to nitrous oxide. Investigations have shown that in most alternators it is formed by local discharge between the outer liner of the stator insulating tube and the edge of the core laminations in the stator slot. The discharge produces pitting of slot liners of fibrous material but has practically no effect on mica. So far as the author is aware no difficulties due to this phenomenon have occurred in large high-voltage alternators.

Ozone is eliminated to a large extent by coating the outside of the slot liner with a semi-conducting material such as a thin layer of graphite or asbestos tape.

Operating experience with ozone was recorded in the discussion on a recent paper on power-station practice.[12]

A test was made in 1935 on a concentric-conductor high-voltage alternator in order to determine whether there was any discharge in the end windings.[4] The alternator was excited to normal voltage and to over-voltage, and the windings observed in complete darkness for a period of 15 minutes. No signs of discharge could be detected by the eye or by means of a camera. Had there been any appreciable discharge in the windings, it would have been detected during this test.

PART 3

EXPERIENCE IN CONNECTION WITH SYSTEM OPERATION

(1) General

The characteristics of the high-voltage alternator are similar to those of the conventional low-voltage construction, and high-voltage machines involve no new operating problems. The only difficulties which have arisen have been due to triple-harmonic circulating currents causing telephone interference or overheating of earthing resistors. Similar difficulties have been experienced for a long time in lower-voltage systems, and the remedy has usually been simple.

In 3-phase systems the third and multiples of the third harmonic are eliminated in the line-to-line voltage but are in phase in the line-to-neutral voltage in all three phases. The remainder of the harmonics sum up to zero at any instant in the three phases, and under normal conditions cause no difficulty. The sum of the harmonics in both high- and low-voltage machines is small, being of the order of only 1 % at no-load and increasing to a value of about 5 % at the maximum output.

As the triple-harmonic voltages appear only in the phase voltage they would have no harmful effect if the system were operated with the neutral point isolated. In practice, however, it is necessary for the safe operation and satisfactory protection of the system to connect the star point to earth. For a long time it has been the recognized procedure, with generators directly connected to the system, to earth the neutral point of only one machine at a time, in order to avoid completing a circuit in which a current could flow due to triple harmonics. The neutral point of the largest alternator connected to the busbars is usually selected for the earth connection.

In order to limit the short-circuit current caused by a line fault to earth a resistance is usually inserted in the neutral connection. A reactance is seldom employed for this purpose in modern systems except in the form of the arc-suppression coil, which is used largely in Continental practice and to a limited extent is finding favour in other parts of the world.

Usually an earthing resistor is designed to pass the full-load current of the alternator at full phase voltage. Thus, even if the system is provided with a second earth point or if it includes a large directly connected network of cables or overhead lines having a high capacitance to earth, the impedance of the neutral circuit is still comparatively high. The impedance may be further increased by the reactance of machine or transformer windings. The circulating current produced by the harmonic voltage is therefore usually small and there is little danger of overheating of windings due to this cause. Earthing resistors have a short-time rating, and occasionally overheating has occurred. The liquid type of resistor, which has a high negative temperature coefficient, is more liable to be affected in this way.

Although the harmonic circulating current is small in comparison with the load current, it is very large in comparison with the current used in communication circuits. If the path of the circulating current through the system network lies in close proximity to telephone or telegraph circuits, there is a possibility of interference. In these circumstances it may be necessary to transfer the earth connection from the alternator to the neutral of a star-connected transformer. A transformer is not likely to give rise to difficulties due to third harmonics, as one winding is normally delta-connected; if the main windings are both star-connected, a delta-connected tertiary winding is usually provided. Where the neutral point of a transformer is not available for earthing, a special earthing transformer may be provided.

The co-ordination of communication and power circuits has been the subject of intensive study for many years and, where the recommended precautions are taken, difficulties due to telephone interference from harmonic currents seldom arise. They are more liable to occur in communication circuits embodying an earth

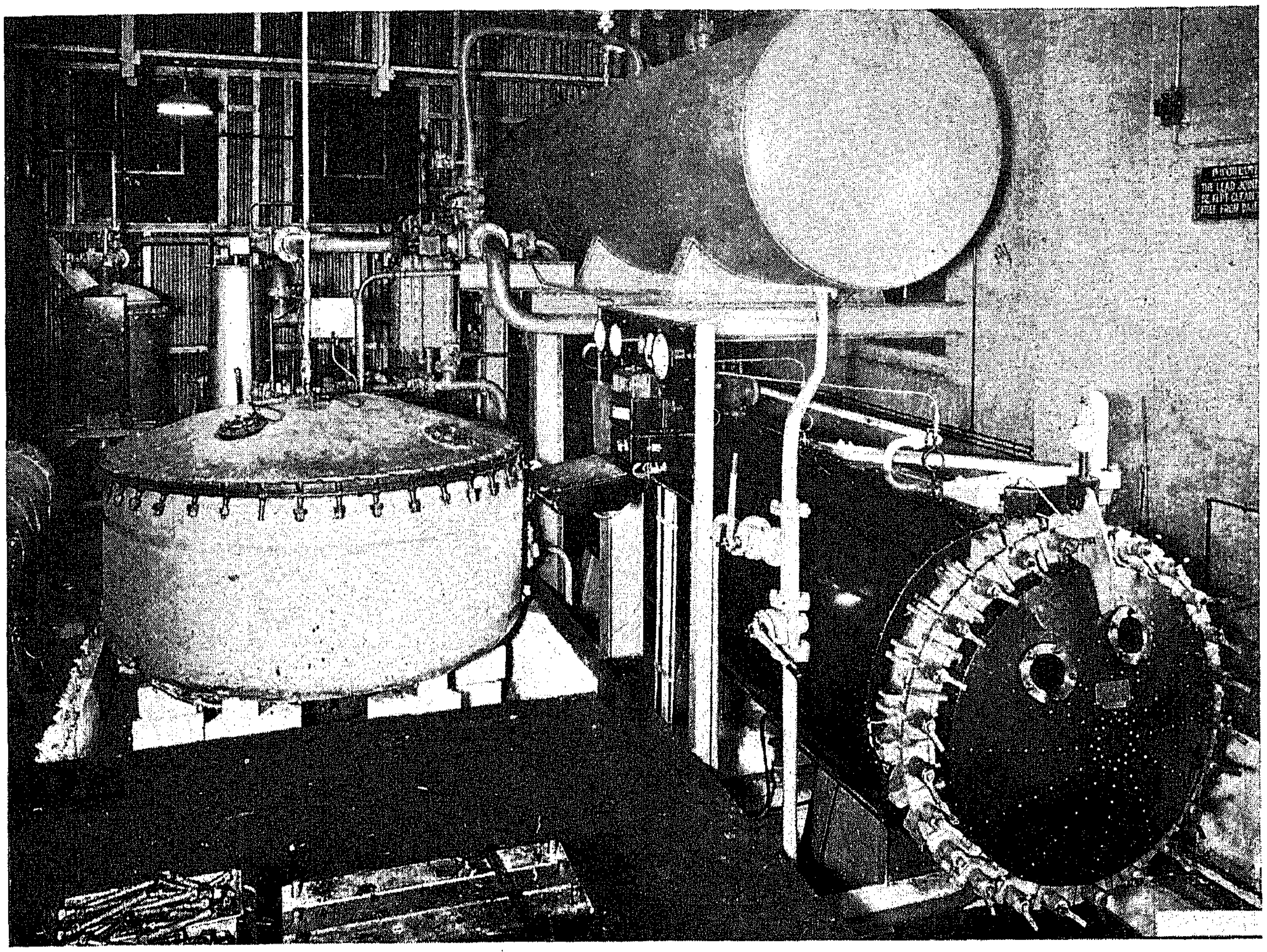

Fig. 5.—Impregnating plant for conductors and coils.

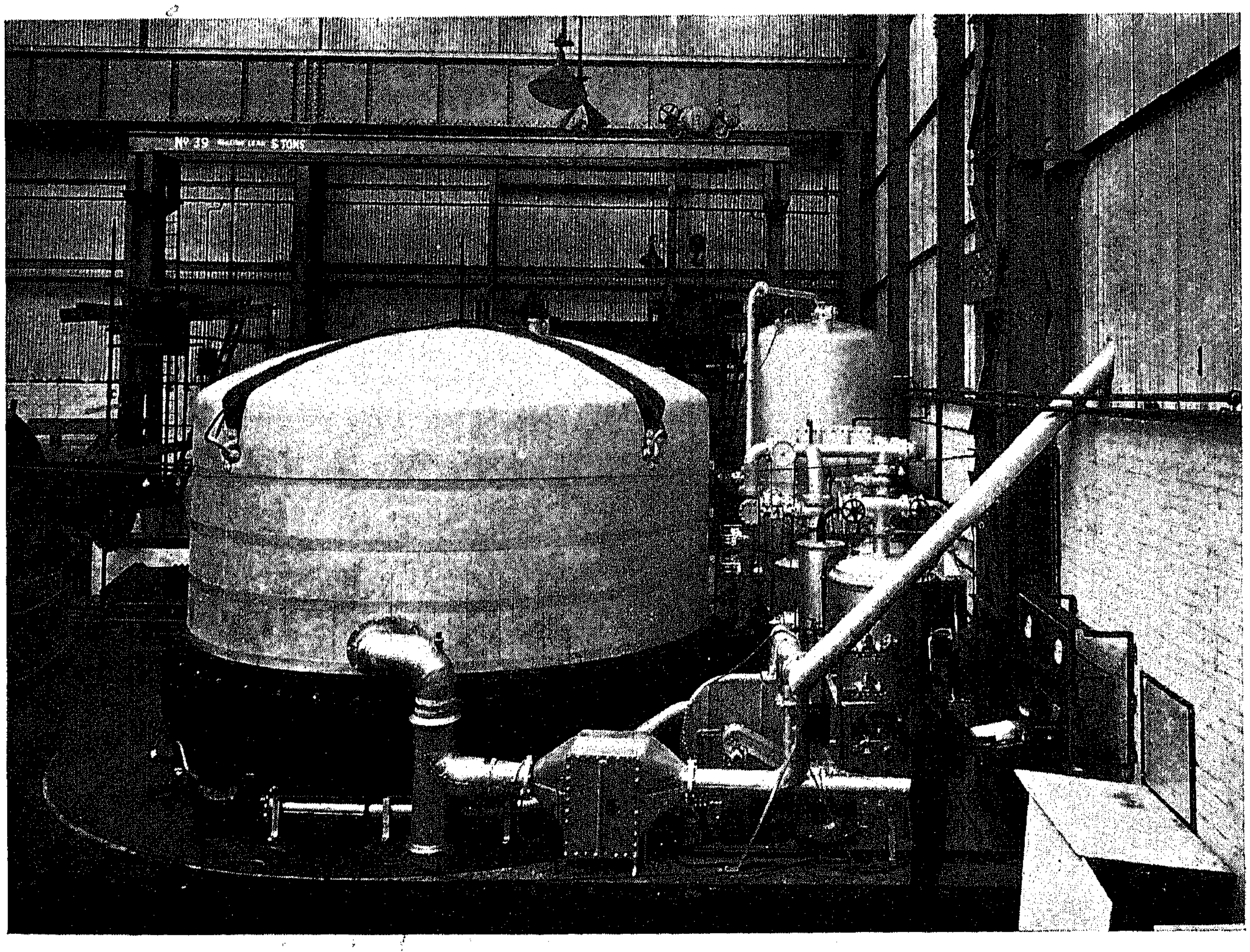

Fig. 7.—Impregnating plant for complete stators.

return, which nowadays is rarely used. In modern communication systems interference from power circuits is caused mainly by fault conditions.

(2) Earthing of 33-kV Systems

Owing to the growth and interconnection of modern systems, occasionally it has been found necessary to earth the system at more than one point and thus it has not been possible to adhere to the principle of selective earthing. The neutral points of two or more transformers may be earthed without much danger of circulating currents, but it may not be permissible also to earth the neutral of a directly-connected generator.

There is no objection to operating a 33-kV concentric-conductor alternator with an insulated neutral. The insulation to earth is ample to withstand the over-voltages which occur in service. The only precaution it is necessary to take is to avoid the possibility of neutral inversion, as explained in Part 2 of the paper.

When only one earth is provided the disconnection of the earthed apparatus due to the operation of the protective gear, or for any other reason, results in the isolation of the system from earth. This possibility exists wherever selective earthing is in use, and normally is accepted by operating engineers. Even where more than one earthed point is provided the opening of an interconnector may isolate part of a system to which only generators are connected, and which is not earthed for the reasons already given.

There seems to be no strong objection to running a section of the system unearthed for the short time required to make suitable switching operations for the restoration of an earth connection. As mentioned above, the acceptance of this condition has been quite general in the past, but recently some engineers have preferred to adopt some form of safeguard. The argument advanced is that the isolation of a system is likely to arise from fault conditions, and with an isolated system dangerous voltage transients may be caused by an arcing earth.

One method, which has been employed on low-voltage systems, is to provide an earthing transformer on the part of the network to which only generators are connected. The earthing transformer has the disadvantage of being expensive. Another solution which is in satisfactory use in a few power stations is the connection of a plain or a paper spark-gap between the generator neutral-point and earth.

In some 33-kV systems more than one earth point is provided and the neutral switches are interlocked. In the event of part of the system being isolated from the main section, which is earthed, a neutral earthing switch in the isolated section is automatically closed.

(3) Arc-Suppression Coils

The earthing of systems through a tuned reactor or arc-suppression coil has received greater attention in this country in recent years, and is being given a trial on a number of systems. The operation of the coil has been fully described in the *Journal*.[6] As the coil has a comparatively high impedance, circulating currents due to harmonics should be negligible and therefore it would be permissible to earth the neutral point of a generator by this means. There is no objection to the use of arc-suppression coils in conjunction with high-voltage concentric-conductor alternators. In the event of a permanent earth fault occurring on the system the effect of the coil is to maintain indefinitely the neutral point of the system at phase potential above earth. In the 33-kV concentric-conductor design the maximum potential of an outer conductor to earth, with one terminal earthed, is limited to 23 kV. The thickness of the insulating tube normally provided is ample to withstand this condition.

Two 20 000-kW 22-kV concentric-conductor alternators have been operating in South Africa for 2½ and 5 years respectively on a system with the neutral point earthed through tuned reactors.

The main advantage of the arc-suppression coil is that by this means it is possible to extinguish transient flashovers to earth on overhead lines, thus preventing circuits from being unnecessarily disconnected. In Continental practice the coil is kept in circuit for permanent as well as transient faults. In this country the general opinion seems to be that the disadvantages of operating a large system with one phase earthed would outweigh the advantage of maintaining continuity of supply to a small section for a few hours.

In the event of it being found advantageous to use arc-suppression coils, arrangements would probably be made automatically to shunt the suppression coil with a resistor if the fault persisted for more than a few seconds. The normal protective apparatus, which has been developed to a high degree of reliability in this country, would then come into action.

The simpler method of leaving the coil in circuit for any type of fault would probably be limited to rural lines.

(4) Protection of High-Voltage Alternators

The standard type of differential protection has proved as satisfactory for high-voltage alternators as for low-voltage machines and transformers. Usually this apparatus is arranged to trip the main and neutral oil circuit-breakers as well as a field-breaking switch.

The use of inter-turn protection has often been proposed for both low- and high-voltage machines, and if reliable apparatus at a reasonable cost were available it would be of particular value for machines having a large number of conductors in one slot. In order to detect a fault between turns a sensitive protective device is required. Various schemes have been proposed, but in general they are rather complicated and may involve tappings to the machine windings, which cannot be regarded as good practice. The concentric-conductor alternator has the advantage that, owing to the disposition of the windings, the normal insulation between turns is ample and requires no reinforcement. This contention is borne out in practice by the reliable operating experience obtained with this type of winding. Only one failure between sections has occurred, and with the improvements which have been made in the joint insulation no further difficulty need be feared.

In a concentric-conductor winding a failure between turns in one slot short-circuits one-third of the winding, and the problem of inter-turn protection is greatly simplified. A form of inter-turn protection using wattmeter-type relays and requiring no tappings to the stator winding has recently been developed on Tyneside which should be suitable for the concentric-conductor type of winding.

Experience has shown that the damage which is caused by an earth fault in an alternator is small, as the differential protection trips both the main and the neutral breakers very rapidly, thus interrupting the fault circuit. A fault between phases causes greater damage, as the fault circuit cannot be interrupted, and although the field circuit may be opened rapidly an appreciable time is required for the main flux to collapse.

A 3-phase circuit-breaker in the star point of the stator windings in addition to the main circuit-breaker would effectually interrupt a fault between phases, but in view of the rare occurrence of faults of this type it is not usually justified economically.

CONCLUSION

In this paper the operating experience with concentric-conductor high-voltage alternators has been reviewed; it is felt that a full and frank account of the difficulties met will be of benefit to operating engineers, consultants, and manufacturers alike.

Full advantage has been taken of the experience gained in effecting improvements in design, construction and manufacture, and also in the testing and inspection of materials and parts during manufacture.

It may be claimed that the excellent performance of the first concentric-conductor alternator over a period of 11 years is ample confirmation that the principle of the design is sound. The operation and reliability of concentric-conductor alternators has in general been satisfactory, and there are no doubts as to the future of high-voltage generators.

ACKNOWLEDGMENTS

The author is indebted to the Directors of Messrs. C. A. Parsons and Co., Ltd., for their permission to publish the information given in the paper, and to many of his colleagues on the staff for their assistance in the preparation of the paper.

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WRITTEN CONTRIBUTIONS TO THE GENERAL DISCUSSION ON THE ABOVE PAPER

Mr. J. W. Howard: In dealing with large and important units it should obviously be the principal aim of the designer to provide ample margins of safety at the points where abnormal conditions of operation are likely to cause distress to insulation which may be ample for the machine under normal working conditions.

One of the principal features of the author's design is that the insulation is graded, only the bulls being insulated for the full voltage, the conditions being that:—

$\frac{1}{3}$ of winding is insulated for 33 000 volts
$\frac{1}{3}$,, ,, ,, ,, ,, 22 000 volts
$\frac{1}{3}$,, ,, ,, ,, ,, 11 000 volts

The only operating condition under which such a construction is fully justified is when the neutral point is adequately earthed. As described in the paper, this fundamental condition has been neglected in many cases, in spite of the fact that it is well known that as soon as the neutral is isolated any surge voltage set up during switching may cause the neutral point to rise to an excessive voltage, a condition particularly dangerous when graded insulation has been adopted by the designer. Graded insulation has been tried in the design of large transformers, but unless the fundamental condition of adequately earthed neutral is rigidly observed, experience with such designs has led to their being regarded with disfavour.

Dealing with safety factors for abnormal conditions, in a stator winding of "normal design" the principal danger caused by surge pressure is that due to the steepness of the wave front. This causes high transient pressures between adjacent turns, but fortunately this circumstance can easily and adequately be taken care of by suitably increasing the turn insulation. These larger machines have only a small number of conductors per slot, and the turns can be separately insulated with the full thickness of the micanite to earth with only a relatively unimportant increase in the slot depth.

In the case of the machine with concentric conductors the wave front is not so important, although, owing to variation in admittance between the 3 conductors per slot, the surge voltage is by no means equally distributed between the 3 sections of the winding. What is of vital importance is the fact that the coupling of the 3 separate sections sets up travelling waves within the stator winding itself, and this may give very high transient stresses under certain conditions. The incidence of such waves is largely determined by the shape of the surge tail.

With the concentric conductor, for many reasons it is difficult for the designer to increase materially the insulation between the sections of the winding, and in any case an increase to the full insulation to earth as carried out on the normal winding is well-nigh impossible.

Dr. M. L. Kahn: The paper reveals some observations which seem to be in complete accord with a theoretical investigation carried out on the subject of the behaviour of concentric windings stressed by travelling waves. The following results of this investigation may be indicated here in anticipation of its publication later.

(1) The stresses between adjacent turns are approximately the same and depend equally on the surge impedance of the line and on the terminal pressure to earth of an ordinary winding with the same surge impedance as that of the concentric winding.

(2) The maximum terminal voltage cannot be calculated from the ratio between the surge impedance of the line and that of the winding in the usual manner. It is always increased above that initial theoretical figure, so calculated, by waves which are reflected once inside the winding and a second time at the terminals.

(3) When being operated with insulated star-point the concentric winding is subjected, like any other system comprising an " open end," to a voltage stress of approximately twice the amplitude of the incident wave. This applies theoretically independently of the ratio of the surge impedances for waves of infinite tail length. The ratio between the maximum star-point voltage and the voltage of the incident wave, found if no damping is taken into account, was 2·5. The damping and the finite tail length will reduce this figure to a certain extent. The insulated star-point remains, however, a highly stressed part and requires full insulation to earth as much as any star-point of a transformer operating with insulated star-point. This probably explains the breakdowns from the " outer " conductor to earth, especially in those cases where neutral inversion was impossible.

(4) The probability of a breakdown due to travelling waves has a maximum near the terminals and the cross connections between the different stages of the concentric winding, and another just in the middle of each turn. The latter condition agrees with the location of repeated faults shown in Fig. 4 of the paper.

(5) Concentric windings seem especially susceptible to long waves, regardless of the slope of the wave front. Experiments, therefore, can disclose the behaviour of such windings only if made with a sufficiently powerful surge generator. This seems to be the reason why an earlier publication* of experimental results on this subject did not reveal the inner oscillations and voltage stresses which we must expect from the results of the investigation in question.

The assumption that " neutral inversion " is the reason for some of the failures which have occurred may give rise to the question whether there are any eye-witness accounts of troubles which have been ascribed to this cause. The attention of the personnel is very often drawn—visually as well as aurally—to instability due to self-excited amplitude oscillations in saturated iron circuits; the pointers of the voltmeters, especially those of the voltage transformer which was responsible for the trouble, are vibrating with a visible frequency of perhaps 3 to 15 vibrations per second, simultaneously causing a noise which is easily heard in the quiet control room of a power station.

Neutral instabilities have been observed in installations for the highest voltages where the factor of safety against over-voltages is not, of course, as high as in a 33-kV system. However, we do not recall that any direct breakdown has been explained in this way. The probability of voltages many times exceeding the network voltage does not, on account of the nature of saturated iron, seem as great as the probability of the voltage transformer becoming overheated by the rather heavy peaked currents. Thus failures on the basis of neutral inversion have, in some cases we know of, originated in damage done to the voltage transformer, which damage can easily be seen from the melting of the compound filling. Breakdown then occurred only after a considerable time.

Mr. P. Richardson: In a paper dealing with faults on alternator windings and in particular the failures described in connection with the alternators at Tir John power station, Swansea, it might be well to include further information with regard to routine insulation tests devised to detect incipient faults. As stated in the paper, the failure which occurred on one of the Tir John machines, although initiated by a faulty bush, was ultimately due to progressive tracking, and had routine tests been applied with sufficient frequency the trouble could have been detected before actual failure of the windings occurred.

There is one feature of the concentric-conductor windings which is valuable from the point of view of routine testing and that is the possibility of testing between the turns of the winding in addition to testing the completed windings to earth. There are two methods of test applicable to machine windings, the first being the well-tried but little-understood insulation-resistance test performed with a Megger tester, and the second the more recent method whereby the dielectric loss and power factor of the insulation is measured (sometimes called Doble testing). This latter method of testing has been applied with considerable success to bushings and similar apparatus, but, unfortunately, it is not of any great assistance as far as alternators are concerned. The additional loss occurring at a weak spot in the windings is small compared with the total loss of the windings, and it becomes extremely difficult to detect any incipient fault.

Insulation-resistance measurements normally record the volume conductivity of the insulation, particularly where the windings are in a clean condition and surface leakage can be neglected, but should there be a low resistance between sections of the windings then this parallel resistance will cause the insulation-resistance test value to fall. That this method is a success is illustrated by the example mentioned in the paper where faulty joints were detected in the second stator at Swansea

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* See the discussion on Mr. F. W. Lawton's paper, *Journal I.E.E.*, 1939, **85**, pp. 503 and 513; and also J. Rosen: Paris H.T. Conference, 1937, **1**, p. D11.

Here the faulty joints were detected by observing the disparity between the corresponding sections of each phase; it is unlikely that similar sections of each phase would have faulty joints giving the same insulation-resistance values. In any case a discrepancy would still be observable, as the physical dimensions of each section of the windings must determine the magnitude of the insulation-resistance values.

It is possible, however, to obtain even more information from insulation-resistance tests. It is well known that the insulation resistance of an electrical machine does not attain its steady value until a lapse of anything up to 15 minutes, this being due to the dielectric absorption effect. The rate of increase of insulation resistance gives the relation between the dielectric absorption and the resistance of the insulation. For example, if the windings are damp the insulation resistance will be low and will rapidly attain a steady value but of a low magnitude. In order to measure the rate of increase of insulation resistance with time, a hand-operated insulation tester is not very satisfactory and experience has led to the adoption either of motor-driven testers or of some form of constant-voltage supply. Routine tests carried out on the insulation of alternator windings at regular intervals of 6 or 12 months indicate the condition of the insulation, and comparisons with previous figures show whether the insulation level has deteriorated or whether it is following the observed effect of improving with time.

There is more to be gained from the intelligent use of a Megger tester than is realized by many operating engineers, and as research on insulation problems continues it will be possible to obtain still more information from such routine tests.

[The author's reply to this discussion will be found on page 364.]

DISCUSSION BEFORE THE MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, 11TH DECEMBER, 1939

Prof. E. W. Marchant: The concentric-conductor type of alternator described in the paper is of interest, because it is the first application that has been made of a principle, well established in connection with cables, to the winding of machinery. The inter-sheath cable has been known for many years, but it is only comparatively recently that it has been applied to the winding of alternators, and the manufacturers of these alternators are to be congratulated on solving the difficult problem of the jointing of turns.

It should be noticed that the volume of insulation required to protect a conductor against any given voltage with a given permissible electric stress in the dielectric, becomes smaller as the size of the conductor decreases. Further, the insulation covering a conductor of larger diameter will usually break down with a smaller electric stress than the same insulation on a conductor of smaller diameter. Hence, for two reasons, the use of conductors of large diameter is less economical from the point of view of insulating material than the use of conductors of smaller diameter. On the other hand, the sub-division of the voltage by the concentric-conductor arrangement leads to greater effectiveness in the use of the insulating material. I should be interested to know how the space factor of an alternator with a concentric conductor compares with that of one wound with the conductor coils encased in insulating tubes.

There is one point on page 352, in connection with the operation of the alternators, upon which it may be worth while to lay some stress. The generation of ozone and the smell of ozone in the vicinity of high-voltage alternators is not necessarily an indication of any defect in the insulating material. It is, of course, undesirable, because ozone, or more probably nitric acid, is likely to have a deleterious effect on the insulating material. But if there is a pocket in the insulation not filled with impregnating material there may be a discharge in the pocket, even if there is no evidence of any defect on the surface. In the ordinary pattern of ozonizer a high-voltage discharge is produced between two insulating plates, although no ozone or nitric acid is produced at the surfaces of the plates themselves. The same electric flux passes across the air-gap between the plates as through the slabs of insulating material, but since the specific inductive capacity of the slabs is larger than that of the air the electric stress in them is much less; consequently with a material like ebonite or micanite with 3–4 times the specific inductive capacity and a greater electric strength than air, it is possible to produce a stress between two slabs of insulating material which is large enough to break down the air between them and cause brush discharge, although the stress in the insulation itself is well below breakdown value. Energy can be developed in this space in the form of brush discharge, although the space is separated from the terminals of the supply by insulation in just the same way as it would be in a resistor connected between two capacitors in series. A brush discharge, therefore, may be produced in a pocket in the insulation, even if there is no evidence of brush discharge at the surface.

Another point to which I should like to refer is the triple-frequency currents which may flow in the conductors connecting the neutrals of two alternators. We investigated this several years ago at the Lister Drive power station, where two alternators of different design were connected in parallel, with the neutrals also connected. It was found that the current through the neutral was about 25% of the full-load current through the alternator winding, and when this was examined with an oscillograph it was found to consist almost entirely of triple-frequency currents. This large current does not heat the windings as much as might be expected. For example, if the triple-frequency current in a winding is 20% of the fundamental, the additional heating is only 2%. These currents may, however, cause defects in the operation of protective gear, and such troubles often occur in connection with transformer substations.

I am interested also in the author's reference to the method of earthing the neutrals of alternators, through Petersen or arc-suppression coils. I came across Petersen coils first in the Ardnacrusha power station of the Shannon scheme, where they were used to suppress arcs which might occur if one phase of the overhead line of the system went to earth. The use of these coils in this country has not hitherto been extensive. They have considerable advantages, but if a fault occurs on one phase, the voltage of the neutral becomes equal to the phase voltage and that of the ends of the other two phases of the winding becomes equal to the line voltage. It seems to me that the earth resistor is a safer arrangement for earthing the neutrals of alternators than the arc-suppression coil, and also that there is a good deal to be said in favour of earthing the neutral of only one machine in a power station, so as to avoid the flow of currents through neutral interconnectors inside the station.

Mr. G. A. Juhlin: The company with which I am associated has always taken the view that it is of general benefit that operating troubles should be freely discussed, as if this is done it is possible to prevent similar difficulties from being experienced several years later.

On page 347 the author refers to a breakdown on a 33-kV machine due to creepage along the surface of the conductor to the stator core; the breakdown was assumed to have been caused by over-voltage. I take it that as the machine was connected to a system the neutral point of which was earthed the failure could not have been due to neutral inversion.

The explanation given for the pitting of the metal bases of the insulators is very interesting. I presume that, as the machines were on load when the breakdown took place, neutral inversion could not have been responsible for the stator-winding failure.

It is interesting that trouble should be experienced with salt deposit in closed air circuits. We have many installations in coastal situations, but have never had any difficulties of this sort. It would be interesting to know whether the author has found other cases where salt has been deposited in a closed air circuit.

One of the most interesting statements in the paper is that failure of the insulation of a conductor to earth has occurred in only one alternator, and that this failure was attributed to insufficient thickness of insulation. This is in accord with the view which I have always held, namely that if any difficulty occurred with high-voltage machines it would be associated with the end windings.

Mica insulation, properly applied, will give an ample margin of safety; but the problem of the creepage distance is much more difficult. That problem cannot be solved merely by increasing the creepage distance, as dirt will accumulate and reduce the value of the creepage distance.

A question that suggests itself is whether any advantage sufficient to balance the difficulties is obtained from the concentric conductor. I am of the opinion that a winding which can be fully insulated throughout its length possesses great advantages, as its effectiveness need not depend on creepage surfaces being kept clean. The potential gradient through the slot insulation can be satisfactorily taken care of by grading shields, in the same way as is adopted in condenser bushings.

I am in agreement with the author that it is desirable to avoid air spaces including creepage surfaces, but I do not share his optimism that they can be avoided by the use of varnish impregnation. Experience shows that it is very difficult to fill interstices with oxidizing varnish (which the author states is used), as the thickness of the varnish film obtainable from each impregnation is extremely small. For this reason I am of the opinion that it is necessary to impregnate the coils before assembly with some non-oxidizing compound such as bitumen gum, which renders the insulation entirely moisture-proof. This method has the added advantage that machines can be wound on site, or repairs carried out, which is impossible if the completed stator must be impregnated.

Mr. H. Pryce-Jones: The successful working of the alternators after the modifications had been made indicates the correctness of the diagnosis of the various breakdowns. The difficulty of accurate diagnosis is well known to those who have had to investigate such faults, as the evidence of the original fault is so often completely destroyed by the resultant power arc.

I am surprised at the number of large 3 000-r.p.m. machines which appear in the Table on page 346. I myself would be very cautious about installing such large high-speed machines. Has any commutation trouble been experienced on the exciters of these large 3 000-r.p.m. machines?

On page 348 reference is made to moisture in the air ducts; I also have experienced this trouble, and have overcome it by reducing the water flow in the coolers, thereby preventing condensation.

The author's statement on page 349 supports the view that high test voltages are to be deprecated. Such tests give little guidance as to how near the machine is to breakdown at the close of the test, and I am of the opinion that the Schering-bridge test is the only true method of measuring insulation safety.

On page 351 and elsewhere the author refers to phase-isolated switchgear. I assume that he is referring to metalclad gear and that phase isolation is taken to the limit, even to the voltage transformers. While agreeing with the principle of phase isolation, I think this is going too far, particularly as it gives no option but to earth the voltage-transformer high-voltage windings.

In the undertaking with which I am associated we are strong advocates of cellular-type switchgear, and we obtain complete phase isolation with the exception that the voltage transformers are connected across phases.

The author's reference to ozone is interesting; I also have come across this effect, but as far as can be determined there is no evidence of discharge on the alternator windings.

Mr. J. E. Macfarlane: During the cold snap of Christmas, 1938, there were several failures of the supply at Brimsdown, but they were not due to the alternators.

With regard to the construction of the windings, and especially the end windings of the high-voltage alternators, one must do something as in cable work to prevent breakdowns due to voids in the winding or between the coil insulation and the core. It would be interesting to know whether this class of winding would be suitable for the synchronous phase-modifiers which have been made by the author's firm.

If hydrogen cooling were adopted, with a separate cooling section giving a higher pressure on the end winding, would it be possible to obtain higher voltages and to get the effect that is now obtained on gas-pressure cables?

Mr. W. N. Kilner: The joint construction shown in Fig. 3 indicates that in making a joint between the "inner" slot conductor and the end connector, a loose copper sleeve is first fitted over the insulation of the "bull" conductor; the wires of the "inner" conductor are then placed on this sleeve, and the loop of the end connector fitted over the wires. The sleeve, slot conductor, and end connector, are then all sweated together, and the micanite bush (Fig. 6) fitted between the copper sleeve and the "bull" conductor insulation. The fitting of this bush and the insulating of the right-angle joint between the slot conductor and the end connector must demand a very high standard of workmanship, and it would appear that the effectiveness of the bush in preventing flashover between conductors depends entirely upon the sealing of the insulation by the subsequent impregnating process, described on page 350.

With reference to earthing of the neutral point, the author mentions on page 353 that while certain engineers have recommended this he does not consider it necessary. I would suggest that, while it is not essential, it is desirable; for, as is shown in the paper (Fig. 2), on one occasion a machine which was intended to be earthed during running-up and shutting-down periods, became isolated owing to a transformer having failed, and as a result there was later a breakdown on the 33-kV alternator.

In order to reduce the voltage value to which the neutral end of the winding can be raised, as the result of inversion or surges, we have always recommended that the neutral be earthed permanently through a moderately high resistance, as the cost of this is small. The only objection is that mentioned by the author, namely interference with communication circuits, caused by the flow of triple-harmonic currents. The value of the triple harmonic in the voltage wave of the 33-kV alternators built by the firm with which I am associated is of the same order as the figures given by the author, and no complaints of its having caused interference have been received from operating engineers.

Reference is made on pages 353 and 354 to inter-turn protection; this is generally regarded as unnecessary in the case of lower-voltage machines, where the insulation between turns is relatively less than in the case of most 33-kV generators.

It is feasible to design 33-kV windings with only one turn per coil, in which case each turn is fully insulated to earth, and the insulation between turns is therefore greater than the insulation to earth. This is a feature of the windings of which I have experience, and no additional safeguard would be provided by fitting them with inter-turn protective gear.

[The author's reply to this discussion will be found on page 364.]

DISCUSSION BEFORE THE NORTH-EASTERN CENTRE, AT NEWCASTLE, 22ND JANUARY, 1940

Mr. F. C. Winfield: It is axiomatic with engineers that no new developments in the art ever occur without teething troubles. The 33-kV machines which the author and his colleagues produced seemed, however, in their early years to disobey the usual laws and it was several years before any real troubles occurred. It was about this period that I became more closely associated with these high-voltage machines on the user's side and I have, therefore, a close acquaintance with the troubles which occurred and the remedies which have been applied. I have read through the author's explanation of the troubles, which is very clear. I am reasonably satisfied that the Brimsdown examples were due, as he states, to neutral inversion, but I do not feel quite so positive about the South African troubles. Here quite clearly neutral inversion could be present, and I feel it reasonable to assume that this was one cause of the trouble. On the other hand, the evidence does leave it open to say that there may have been other contributory causes in the form of impaired insulation either during the manufacture and erection period or possibly even by dirt ingress later, or both. In other words, I feel that neutral inversion was probably the trigger which exploded the mine, but that it may have been assisted by weaknesses in other directions. However, I have been in close touch with the modifications in design and manufacture which the author and his colleagues have introduced since that time, and I think I can safely say that however good the record of the early Brimsdown machines may be there is no doubt that the author's modern production is a very much superior article.

Regarding neutral inversion, I imagine that instances of this have occurred in the past more frequently than we have realized but that the disease has not been recognized and has been given other names. However, its cause is now understood and the preventive measures are also understood and not difficult to apply. For this reason I see no necessity to complicate the normal earthing problem or to introduce special switching operations to deal with neutral inversion. I certainly consider it undesirable to add to the number of things which an operator has to do when switching a machine, and I think that the range of remedies is sufficient to make this unnecessary. Hence I see no reason why neutral-inversion troubles should give us further concern. Given this and the general improvements in design recorded in the paper, I think we may reasonably hope that the future record of 33-kV machines of this type will be at least as free from trouble as lower-voltage machines in comparable service.

The author refers to the use of 3-phase neutral earthing switches in order to open all 3 phases. I have considered this arrangement on many occasions and would not hesitate to employ it if the circumstances seemed to justify it. However, experience to date has not seemed sufficiently pressing to justify the additional cost which would be involved. It will be appreciated that not only the additional cost of switchgear is involved but the accommodation for this and the frequently very heavy 3-phase cabling necessary to couple it up.

I can confirm the author's remarks about the presence of ozone or nitrous oxide. This is not uncommonly met on machines of 11 000 volts and upwards and is to-day not viewed with any alarm whatever.

The author implies in certain of his remarks that there are no fundamental differences in technique between high-voltage and low-voltage machines, other than the grading adopted in the former. I think it is worthy of note that the grading does lead to one fundamental difference, and that is that whereas the windings of moderate-voltage machines proceed progressively round the core in such manner that the voltage between turns is very small, in the graded high-voltage machine essentially the winding doubles back on itself in such manner that the voltage between two adjacent turns in one concentric conductor corresponds to that of many turns in the winding. Hence the nominal possibility of faults between turns is much higher in the graded machine than in the non-graded.

On the other hand, the author has done a number of experiments to show that the distribution of transient high-frequency voltages through his type of winding is very uniform indeed and very much superior to that with the lower-voltage machines. I think that whilst his paper is primarily a record of experiences it does justify drawing attention to fundamental differences and that the addition of this curve of voltage distribution to the paper would be much appreciated.

In conclusion, I have given some thought to the question of what is the scope of these higher-voltage machines. It is at last becoming recognized by supply engineers that the association of generation switching with major distribution systems, as distinct from the transmission or bulk-supply system, is bad economics. Accordingly it is fairly clear now that very few major stations will occur in future, in this country at least, switching at any voltages lower than 33 kV. In other words, the voltages of switching in our major stations in the future will be 33 kV, 66 kV or 132 kV, and possibly even higher. At the moment 33 kV seems to be finding much favour, but I have the feeling also that even 33 kV is tending to become a major distribution voltage, that this phase will not last very many years, and that voltages of generation switching will soon be 66 kV, 132 kV or more. Since the voltage of switching decides essentially whether direct high-voltage generation is worth while or not this point may be important, and it may in fact suggest to the author the desirability of prosecuting his 66-kV designs even more vigorously in order that experience may be gained.

Mr. H. Leyburn: The author describes 7 breakdowns of 4 different alternators, some of which he attributes to faulty conductor or joint insulation and others to neutral inversion. I have no doubt that the measures he has taken to improve the insulation of future machines, as described in Part 2 of the paper, will deal adequately with this problem and will prevent future breakdowns due to this cause.

With regard to what the author calls "neutral inversion," I prefer the more general term "neutral instability" as describing more correctly the phenomenon discussed in the paper; and in what follows I shall use the latter term.

In connection with the last breakdown of the Brimsdown machine and more especially with that of the two Cape Town machines, I should like to know whether any site tests were carried out to prove that these breakdowns were due to neutral instability. Alternatively, can the author give particulars (including flux density of voltage transformers) of any laboratory tests he made to obtain such proof? Whether or not this can be obtained, the very fact that the possibility of neutral instability has been raised makes it necessary to take all the steps which will eliminate once and for all even a suspicion of this phenomenon arising.

This brings me to the remedial measures suggested by the author on pages 351 and 352. Anybody not reading the paper carefully may obtain the impression that neutral instability, which, as is common knowledge, can occur only when the generator is running disconnected from the main busbars, is caused by the presence of an earthed voltage transformer connected to the generator and that its elimination presents a difficult problem. This, however, is not by any means the case; on the contrary, the possibility of neutral instability can be eliminated beyond doubt by taking the simple precautions described below.

Before dealing with these I should like to say a few words about the method of preventing neutral instability which the author describes as ideal, namely the isolation from earth of the star point of the voltage transformer. Although this may be "ideal" from the point of view of preventing neutral instability, it is by no means so as regards the general layout of the power-station equipment, in that it runs counter to the principle of phase-isolation. Phase-isolation has long been recognized as being of invaluable assistance in minimizing the effects of breakdowns of electrical equipment operating at all voltages, but particularly at 33 kV and above. It ensures that faults develop as limited earth faults, a fact which makes it comparatively easy to isolate them without undue disturbance of the remainder of the system. In my opinion, the principle of phase-isolation is of overriding importance and must not be abandoned even in isolated cases in order to guard against the remote contingency of neutral instability, particularly as the latter can be dealt with in much simpler ways.

The first measure to adopt to avoid the possibility of neutral instability is so to design the voltage transformer that it runs normally at a flux density much below saturation point. Since neutral instability depends for its existence upon a saturated iron circuit, such a voltage transformer cannot give rise to it. The proof of this statement is given in the papers published mainly in America and quoted by the author in the Bibliography. Further, a resistor may be connected across the terminals of an open delta tertiary winding which puts a load on the voltage transformer in the event of a shift of the generator neutral point, and thus stops a build-up of potential between it and earth. Under normal conditions the resistor has a negligible effect upon the accuracy of the voltage transformer. I consider that either of the above measures in itself is sufficient to eliminate neutral instability, and both measures in conjunction are more than adequate for doing so.

Nevertheless, in order to allay any fears that may still exist in the minds of engineers in spite of these precautions, a simple scheme has been devised which has

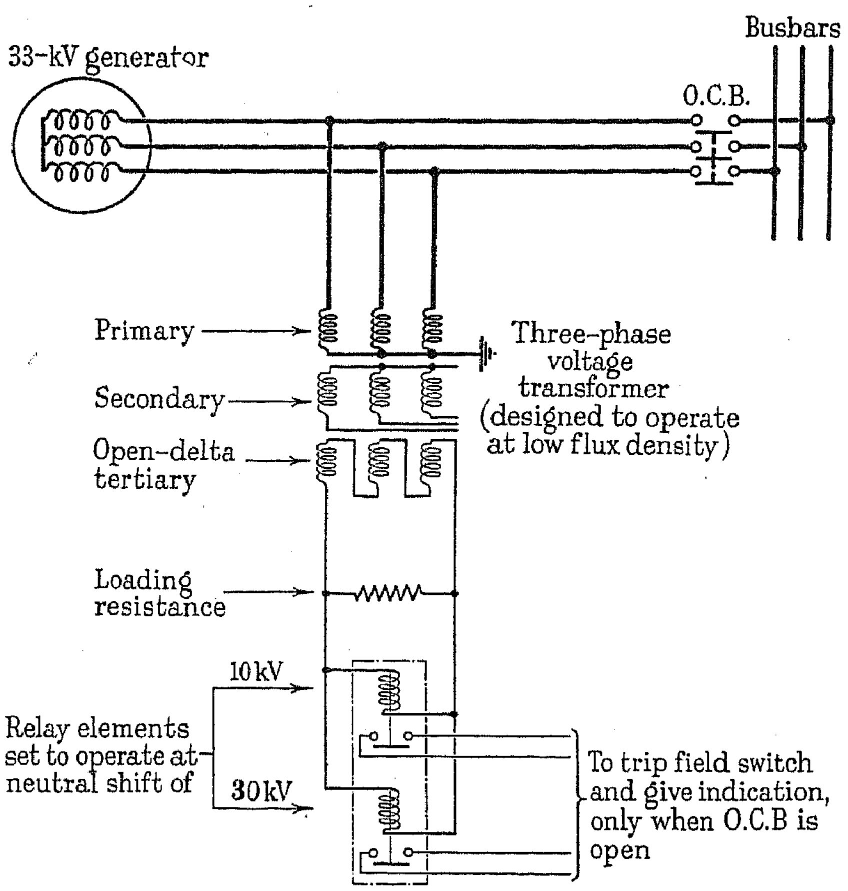
33-kV generator
Busbars
O.C.B.
Primary
Secondary
Open-delta tertiary
Three-phase voltage transformer (designed to operate at low flux density)
Loading resistance
10kV
30kV
Relay elements set to operate at neutral shift of
To trip field switch and give indication, only when O.C.B is open

Fig. A.—Scheme for eliminating neutral instability, applied to a 33-kV generator.

a two-fold object: Firstly, in the very unlikely event of a dangerous shift of the neutral point of the generator, to suppress the generator field; and secondly, to indicate that such a shift has occurred. The application of this simple scheme will prove definitely the absence or presence of neutral instability. The scheme is illustrated in Fig. A. Two relay elements are connected to the voltage transformer in such a way that they operate whenever the neutral point of the generator is displaced. The amount of displacement, as indicated by these relay elements, determines whether it has been due to an ordinary fault condition or to neutral instability. It should be added that, since neutral instability can take place only when the generator is disconnected from the busbars, the relay is also so arranged that it comes into operation only when the main circuit-breaker is open. Thus it does not in any way affect the normal running conditions of the generator, and cannot be regarded as additional protective equipment in the ordinary sense.

It has been suggested by the author that in addition to these measures the generator should be earthed while being run up before synchronizing and again after it has been taken off the busbars. I consider this additional precaution unnecessary and do not welcome it because, while it may not do any harm, it complicates the operating conditions and is dependent on the human element.

With regard to the general question of system earthing, discussed in Part 3 of the paper, if it is found impracticable to earth the neutral point of the 33-kV generator itself because of harmonic currents, I prefer to see an earthing transformer installed. This can be associated with the generator it is intended to use for earthing and should be connected to earth through a resistor in accordance with usual practice.

I cannot agree with the author's statements in the section entitled "Earthing of 33-kV systems." I do not, for example, consider earthing through a plain or paper spark-gap a satisfactory solution. Apart from the difficulty of designing a suitable spark-gap which will carry the rated earth-fault current for a reasonable time without undue damage, the presence of a fault arc between the generator neutral and earth is to be deprecated. Can the author say what kind of spark gap he has in mind and how it can be made to work satisfactorily under heavy fault conditions lasting an appreciable time, without sustaining great damage or even being destroyed?

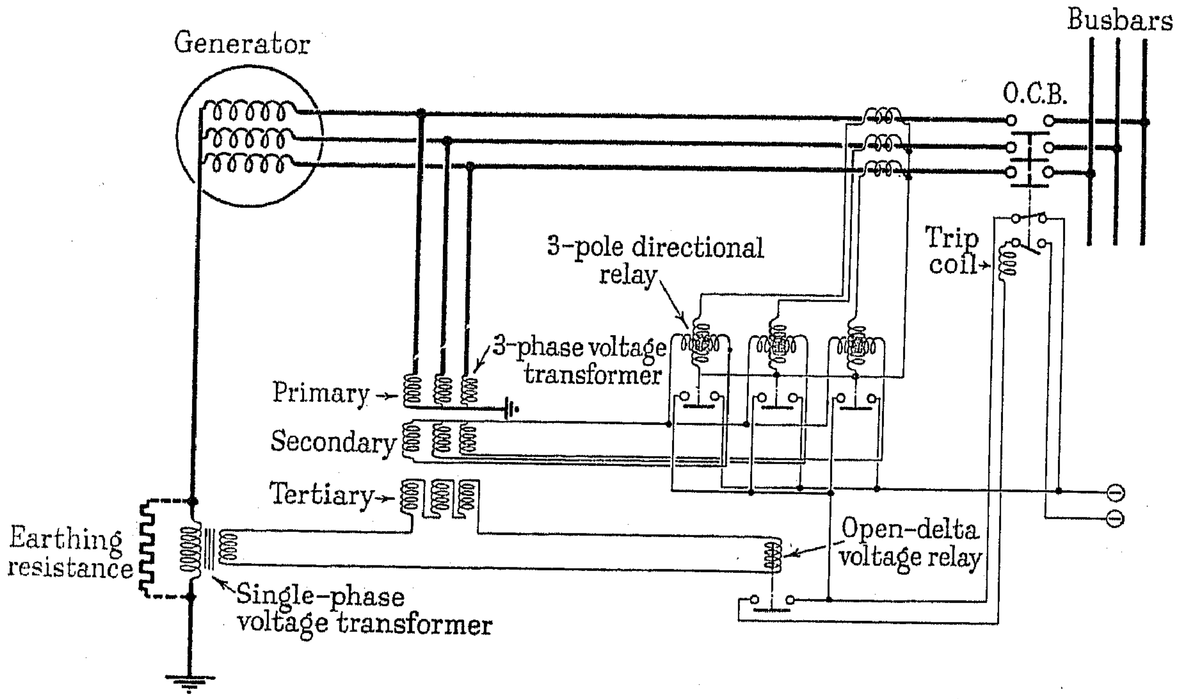

Fig. B.—Inter-turn protection of a generator.

I agree with the author's statement concerning arc-suppression coils, namely that they should be short-circuited after a fault has lasted for some time, in order to allow it to be cleared by the normal protective gear. In other words, the arc-suppression coil should be used for its primary purpose, namely for dealing with transient faults.

As explained by the author, the construction of the concentric type high-voltage generator is such that a fault between turns always occurs across one-third of the whole winding. This makes the problem of inter-turn protection very much simpler than with normally wound generators. The author mentions a scheme of inter-turn protection developed on Tyneside, and this is illustrated in Fig. B. Briefly, it depends for its operation on the fact that when an inter-turn fault occurs power is fed into the faulty generator by the remainder of the system, and simultaneously the voltage vectors are so distorted that a voltage appears across an open delta winding on the 3-phase voltage transformer connected in series with the secondary winding of a single-phase voltage transformer between the neutral and earth. These two conditions are characteristic of an inter-turn fault and are made use of to disconnect the generator when such a fault occurs. Whether or not the addition of the equipment required for inter-turn protection is justified technically and economically, experience alone can tell.

In conclusion I would say that although I have disagreed with some parts of the paper, particularly in connection with neutral instability, there is no doubt in my mind that high-voltage generators of the concentric-conductor type have come to stay and that the few experiences described in the paper have resulted in a great increase of their reliability.

Mr. V. Easton: Neutral inversion, which has caused failure on 3 out of the 4 machines mentioned in the paper, may occur in any installation with earthed voltage transformers when the system constants are suitable and precautions have not been taken. Since there are many installations of this kind, particularly at the higher voltages, it would be expected that the phenomenon would be more frequently experienced. That this is not so is probably due to the precautions taken in the design of the voltage transformers and also to the fact that with a large capacitance, i.e. with any but a comparatively short length of connected cable, the conditions are stable up to voltages in excess of those which are experienced in service. The effect of the additional capacitance is to reduce the slope of the capacitive current shown in Fig. 8 and to shift the total-current curve to the left, so raising the critical voltage above which instability occurs. At the same time it must be emphasized that if this critical voltage is exceeded the maximum voltage which may be built up due to the phenomenon is also appreciably increased, particularly if the transformer saturation is low.

In theory all the preventive measures mentioned in the paper should be effective, but one or two may introduce practical difficulties. Referring to No. 4, the connection of resistance across an open delta winding on the transformers, some investigations were made recently to check the efficacy of this method. For the experiments a 5 000-kVA alternator of normal construction was used and arrangements were made to connect, between the alternator terminals and earth, electrostatic condensers the capacitance of which could be varied in the ratio of 16 to 1 in order to simulate conditions with different lengths of cables between the machine and the switchgear. The neutral point of the alternator was isolated and that of the voltage transformers solidly earthed.

Spark gaps, connected between the 3 line terminals and also the neutral terminal and earth, were set to limit the stress on the stator insulation to a safe value. Tests were first made with the secondary windings on open circuit and it was found that neutral inversion could be readily reproduced under all conditions of capacitance, i.e. with a variation in capacitance or cable length of 16 to 1. Persistent fluctuating voltages up to $2\frac{1}{2}$–3 times the normal operating voltage to earth were recorded on the meters connected between lines and earth, and there is no doubt that the rise in potential would have been even greater if it had not been limited by the continuous flashover of the spark gaps. When the secondary windings were connected in delta closed through a high resistance, the oscillations of the neutral point and maximum potential of the windings above earth were reduced, the effect varying with the amount of resistance in circuit. Sufficient data were obtained to enable the limiting value of resistance to be determined for any given service conditions.

Electrically the connection of a resistor directly between the alternator neutral and earth is equivalent to a resistor across an open delta winding, but the former arrangement is more direct and therefore eliminates some of the possible errors which may arise in the correlation of data obtained from tests with conditions which may be experienced in service. From further tests which were made it was concluded that for a 33-kV system with voltage transformers designed for a low density at normal voltage a resistance of the order of 50 to 100 000 ohms would be satisfactory. This value of resistance is sufficiently high to ensure no difficulty with 3rd-harmonic currents or interference with the normal operation of the system protective gear.

There is one other precaution which may be taken in the operation of the plant. Although it may not be permissible to earth the alternator neutral point through a low impedance when operating in parallel with other plant, there is no reason why arrangements should not be made to earth the alternator when it is excited and disconnected from the busbars. This may be made automatic, or alternatively an operating instruction could be issued to the effect that the alternator neutral should be earthed when starting up or shutting down the plant whenever the load is less than a small percentage of full load.

Mr. G. W. B. Mitchell: Until comparatively recently, neutral inversion was understood by only a few engineers, and it has therefore been given very little attention when considering system connections. I think this is unfortunate, but at the same time there may be some rather natural tendency at present to bring this subject too much into the limelight. Neutral inversion, with all the attendant phenomena which have been described by various authors, can definitely occur under suitable conditions, and when it does the results may be very serious. Furthermore, provided the circuit constants are favourable, as they can well be in practice, it will occur readily. This statement runs contrary to the contentions of certain other engineers, but I can testify to its truth as I was fortunately able to witness the alternator tests described by Mr. Easton and can confirm his statements. It should be remembered, nevertheless, that it so happens that the conditions for the establishment of neutral inversion on a system are rare; and, although this effect should be borne in mind, particularly when considering alternator circuits, its importance relative to such matters as operating convenience and switchgear design should not be exaggerated.

I agree with the author that the ideal method of preventing neutral inversion in alternator circuits is to run the associated voltage transformers with unearthed high-voltage neutrals. This, however, as he states, is not always practicable. Personally, I consider that the most satisfactory alternative is to ensure that the voltage transformer is designed to work at a low flux density, and to equip it with a tertiary winding connected in open delta with a loading resistor across the break.

According to Weller, a voltage transformer which is so designed that it will not saturate when twice normal voltage is impressed across each limb, will prevent the occurrence of neutral inversion under any condition. The provision of the open delta winding and loading resistor is therefore an additional safeguard. I would add that the cost of applying these precautions is not high and is quite insignificant in comparison with the cost of the alternator and the apparatus normally associated therewith.

I should be glad if the author could give some indication or reference in regard to the method used in calculating the magnitude of the over-voltage due to neutral inversion on the second Brimsdown machine.

In regard to the question of inter-turn protection on alternators, it would seem that there is more inherent need for this form of protection on machines employing normal windings than with those employing concentric windings. I agree with the author that it is not practicable to apply inter-turn protection to alternators with normal windings and, in view of the higher factor of safety against inter-turn stresses in the concentric form of winding, I question whether special protection is justifiable in this case either.

Mr. E. C. I. Macdonald: On page 331, col. 2, brief reference is made to the methods adopted to prove that the impregnated conductors comply with the requisite standards. Is the dielectric-loss test supplemented by the information given by the power factor of the dielectric loss? If so, what is the acceptable order of magnitude of the power factor which would be expected from a new conductor?

Does the author make use of the Schering bridge or one of the modifications of it such as are now commonly used for the testing of high-voltage cables?

Is testing of the condition of the insulation carried out at intervals during impregnation, or merely applied as a check test on completion of a given process? In this connection, does the author recommend any form of routine power-factor test or other test on the machine conductors after installation?

Were any loss or power-factor tests carried out on any of the machines on which trouble was experienced, to determine whether any change had taken place in the physical condition of the conductor insulation?

Mr. A. M. Kennedy: The author has devoted a considerable portion of his paper to the interesting and rare phenomena associated with neutral instability. The aspect of the phenomena which I would particularly emphasize is its rarity. The American authorities referred to in the paper agree that four conditions must be fulfilled if neutral inversion is to be at all probable:—

(1) The alternator must not be earthed except through the voltage transformer.

(2) A violent disturbance such as the switching of the voltage transformer on to full voltage must occur.

(3) The voltage transformer must at normal voltage be excited to high flux densities.

(4) The circuit constants must be such as to favour instability.

Both the first condition and the second or third must be present if neutral inversion is to be possible, and for inversion to be at all probable the fourth condition must also be present.

On only one of the four alternators dealt with in the paper has breakdown occurred when the neutral was earthed only through a voltage transformer. In all cases the voltage transformer was permanently connected to the alternator terminals, so that switching cannot have occurred.

The established practice in this country for many years has been to design voltage transformers for very much lower flux densities than those which were used in the U.S.A. Even with the high flux densities which were used in the U.S.A. the authorities found it essential that the knee of the induction curve should be exceeded by the initial surge in the first half-cycle following switching.

The author has not included in the paper any of the circuit constants from which the possibility of neutral inversion was deduced. These would have been of great interest, especially those at Salt River which on examination and re-examination led to exactly opposite conclusions.

It is clear, therefore, that the first essential is fulfilled by only one alternator, the second and third by none, and no information is given as to the fourth condition.

The author's hypothesis is clearly based not on the American conclusions but on the high over-voltages which have been deduced from examination of the nature of the fault. This evidence has, however, also been present when breakdown of the alternators occurred on load, and the cause cannot have been neutral inversion. Some explanation of the evidence, other than neutral instability, is therefore called for.

How the author deduces a voltage of 70 kV from a 4-in. flashover in air and from a surface flashover of 7 in. is not clear. I suggest that such flashovers may not have occurred, but that the physical evidence was caused by creeping of the arc after the fault and not by over-voltages. Were the lead insulators at Salt River tested under running conditions, i.e. in an atmosphere of warm, wet, salt-impregnated air? And may not static over-voltages have caused the arc craters in this instance? To excite and de-excite an alternator sufficiently rapidly to prevent the striking of a power arc seems to me to be an extraordinary feat.

On the strength of this evidence the author's hypothesis would have us believe that not only neutral inversion but a particularly rare variety of it occurred—that in which the neutral oscillates outside the normal voltage vector triangle, a variety which was only produced in America under intentionally favourable conditions in 6 % of the operations switching the voltage transformer into and out of circuit.

Were voltmeters ever used to establish the occurrence of inversion, and were the unmistakable pulse beat, corona, and distress of the voltage transformer associated with this variety of inversion ever observed?

If we set aside neutral inversion for a moment, it immediately appears that the breakdowns were due to inadequate ventilation of the end windings and faulty insulation. It is noteworthy that in all cases end windings, running at a normal voltage of 6·5 kV above earth, were involved; this seems to indicate a local hot-spot, and it would be interesting to know whether in all cases the same phases were involved as were found to be weak at Tir John.

The great precautions in insulation manufacture recently adopted show that the author does not consider the prevention of neutral inversion the solution of all his problems.

In conclusion I would express the hope that power-station engineers will not hastily adopt wholesale precautions against neutral inversion, for such precautions would be very far-reaching. They might involve insistence on even lower flux densities in the voltage-transformer cores, the application of one or more of the protective measures outlined in the paper, and perhaps the addition of special neutral-inversion protective and indicating relays. To avoid these complications engineers might well reject phase-segregated switchgear with all its manifold advantages. Such a retrogressive step, which would affect the whole trend of modern power-station layout, would in my opinion be deplorable. I feel sure, therefore, that electrical engineers will insist on more conclusive evidence of the very existence of neutral instability before embarking upon this vicious spiral.

Mr. W. A. A. Burgess: The author's frank explanation of the troubles experienced with high-voltage concentric-conductor alternators reflects great credit upon him and upon his far-sighted employers, and, at the same time, renders the members of The Institution a valuable service. I should like to ask him whether he considers these alternators less suitable for operation in parallel with more than one neutral earthed than are lower-voltage machines of conventional design, and, if so, why?

What are the comparative amplitudes of higher-harmonic voltages in each case? If the amplitudes of the higher-harmonic voltages and also the mileage of feeder cable connected are considerable, it would appear to be unwise to use liquid earthing resistors, as these are normally short-time rated and boiling may occur. In any case the initial resistance value and the ultimate time rating on the occurrence of an earth fault would be affected.

The reference to the use of glass-silk insulation is of particular interest. I suggest that much more use should be made of this important insulation, both on account of its heat-resisting and transmitting properties and of the greater space factor it permits. The author rightly says that it cannot absorb moisture, but my impression is that it can and does adsorb a considerable amount of moisture and that it is essential that for use as a high-voltage insulation it should be correctly and thoroughly impregnated.

The author devotes some space to a description of a thoroughly scientific impregnating plant. I submit that this is a most essential installation in any factory dealing with high-voltage air-cooled equipment.

I agree with Mr. Winfield that 33 kV is already the lower limit for generation and that much higher generating voltages are likely to be called for in the near future.

I do not consider earthing through a spark gap a satisfactory procedure unless the gap is really capable of welding up with the initial discharge in such a manner as to carry the maximum earth current without danger of interruption. The far-reaching oscillatory results of spark gaps as such are already too well known on the North-East Coast to require further remarks from me.

Mr. R. W. Gregory: To generate large amounts of power at as high a voltage as possible is sound engineering. It is usually better on a power supply system to deal with growth of load by increasing the voltage rather than by increasing the current. In other words, insulation is cheaper than copper per kVA, both in capital cost and in running cost. Excessive current increases the difficulties of control and construction, largely because the mechanical and the thermal stresses in a circuit vary as the square of the current. Circuit-breaker designers, too, although they like a reasonable amount of current to assist their arc-control devices, decidedly object to providing the high rupturing capacity required on modern systems with a low switching voltage.

Wherever possible I prefer the current in any circuit not to exceed about 1 000 amperes, which, at 33 kV, 3-phase, is 57 000 kVA, a reasonable figure for a modern alternator.

To control large amounts of power, high switching voltages are desirable; and if the generator is to be switched direct without the intervention of a step-up transformer, then it is necessary to generate at the switching voltage of the station, which, at the present time in this country, may be 33 kV or 66 kV.

My own view is that the modern generating station is fundamentally a part of the transmission system and that it is better engineering to switch at the transmission voltage and to step-down everywhere for distribution. Whether we shall ever see 66-kV or 132-kV generators, the author is better able to say than I am. We all know that 33 kV is at present a very popular switching voltage. The author has shown that the technique of manufacturing 33-kV alternators is now well understood, and that 11 years' experience has proved that the concentric system of winding can be relied upon to give good service.

The experiences described in the paper of breakdowns caused by neutral inversion are interesting. The phase-isolated voltage transformer was, and perhaps still is, considered to be essential to sound switchgear design. It originated in the days when circuit-breakers were both untested and unreliable and it was sound engineering to take advantage of the reduction in fault kVA obtained by the resistance in the generator neutral. Nowadays, with tested switchgear, I do not think that the phase-isolated voltage transformer is quite so necessary, although, with metalclad switchgear, one transformer per phase in its metalclad earthed container obviously provides a clean and simple layout.

I feel that if the high-voltage alternator is sound technically and commercially in itself, its use will not be hindered by the arrangement of connections of the voltage transformer on the generator switch-panel.

Mr. T. Carter (*communicated*): Not having come across the term "neutral inversion" previously, I took steps after the Newcastle meeting to discover its meaning; and one result is that as a name it seems to me far from appropriate. During the discussion at the meeting words were used implying an "escape" of the neutral from the vector triangle of the generator. I could not imagine an equilateral triangle so deformed that its median point was outside it: but I found that what "escapes" from the triangle is not its own neutral but "earth," with the consequence that the potential of every point in the triangle, including of course the neutral point, is so raised that the triangle remains entirely unchanged in shape and in the relative disposition of its several parts. The analogy I arrived at was that of a kite flying into the air, the length of the string representing the potential of the neutral point. In flying a kite, one does not normally regard the kite as stationary and the earth as receding from it; and correspondingly it seems much more intelligible to talk of the triangle escaping from "earth" than of "earth" escaping from the triangle. I suggest that whatever name is used should contain the word "potential" rather than the word "neutral," since it is not only the neutral point of the triangle that is affected. In trying to think of a suitable term my mind ran through the possibilities of "potential rocketing," "potential skying," "potential soaring," and even "potential larking;" but perhaps as good a name as any would be "potential instability."

THE AUTHOR'S REPLY TO THE GENERAL DISCUSSION AND TO THE DISCUSSIONS AT LIVERPOOL AND NEWCASTLE

Mr. W. D. Horsley (*in reply*): I would assure Mr. Howard that the insulation of every part of the concentric-conductor winding is ample to meet all conditions of operation. Owing to the economical disposition of the concentric-conductor arrangement there is no difficulty in providing sufficient insulation on the outer conductors and connections to withstand the voltages caused by surges and faults with the neutral point isolated. The outer section of the winding is subjected to a pressure test of 40–45 kV to earth.

In a normal design the high voltage between individual turns produced by surge voltages can be met only by the use of ample inter-turn insulation, although the consequent reduction in inter-turn capacitance accentuates the lack of uniformity of distribution of a voltage surge in the winding. Another reason for providing ample insulation between turns is that it is difficult to apply a pressure test between turns in windings of normal design.

It is shown in the references quoted by Dr. Kahn that the initial distribution of a surge voltage in a concentric-conductor winding is practically uniform; the surge-distribution curves are reproduced in Fig. C. The distribution for a transformer winding, which is also typical of a machine of normal design having a number of turns per slot, is shown for comparison. The effect of travelling waves is discussed in reply to Dr. Kahn. Dr. Kahn does not give details of his theoretical investigation of travelling waves in concentric-conductor windings, and it is difficult to understand his conclusions. It is agreed that the maximum voltage set up in any type of winding with the neutral point insulated is increased above the value of the initial surge voltage owing to reflection.

Tests which have been made on a high-voltage concentric-conductor alternator with an insulated neutral point using a surge generator of ample capacity show that travelling waves resulting from internal reflections at the terminal and inter-section points are more uniformly distributed and have a lower value than in the ordinary type of winding. The voltage at the neutral point is greater than the initial surge voltage at the terminal, and in practice the "step by step" build-up of voltage indicated by the transmission-line theory is found to merge into long-period oscillations, occurring at the natural frequency of the windings, which have a theoretical maximum value of $2E$ at the neutral point. The maximum value can only be produced by a voltage surge having an abnormally long tail applied to all three terminals simultaneously. The insulation of the neutral point of the concentric-conductor winding is ample to meet this condition. Only one machine failed between the outer conductors and earth, and, as is explained in the paper, this was due to thin insulation resulting from a fault in manufacture. In practice the incoming surge voltage is appreciably reduced by the ratio of the line and winding surge-impedances, and as a consequence of the practically uniform initial distribution of surge voltage (as shown in Fig. C) the amplitude of the oscillations is proportionately reduced. A small triple-harmonic voltage is introduced by the discontinuity between the sections of the winding, but its effect on the inter-section oscillatory voltage is negligible and there is no abnormal voltage-difference in any part of the windings.

The diagram in Fig. 4 of the paper gives the location of only one particular fault. The other failures of bars on these particular machines were distributed over the phase and only occurred as the result of a pressure test of nearly 3 times the working voltage which was applied in order to eliminate any weak places.

Examples of failures of apparatus caused by neutral inversion are given in the references on this subject in the Bibliography, and the other points raised by Dr. Kahn are dealt with in the reply to Mr. Leyburn and Mr. Kennedy.

I agree with Mr. Richardson that routine power-factor measurements are unlikely to be of value in detecting incipient faults in machines. It is also doubtful whether they would give any reliable indication of the general state of the insulation. From tests made over a number of years on completed machines it is found that power-factor measurements are influenced by a large number of factors and vary appreciably.

A periodical test of the insulation of windings is very desirable, and it has been found that insulation-resistance measurements carefully taken are a reliable guide to the state of insulation provided that due regard is given to temperature and atmospheric conditions. A low insulation-resistance reading obtained on one phase or one portion of a winding is an immediate indication of an incipient fault. It is an advantage of the concentric-conductor winding that this test is particularly applicable, as the winding may be divided into 9 similar sections. The insulation-resistance level will vary according to the conditions prevailing at the time of the test, but any disparity in the values obtained for corresponding sections would immediately indicate that a weakness was developing. This method of testing represents an advance in testing technique equivalent to routine power-factor measurements on switchgear. The test can be made conveniently during the routine overhauls of the set. It may be of interest to record that the insulation resistance of completed alternators treated in the new impregnating plant described in the paper have shown an increase of the order of 10 times the values previously obtained.

Prof. Marchant's statement, that the insulation on a conductor of large diameter will break down under a smaller electric stress than the same thickness on a smaller-diameter conductor, is not clear; if the average potential gradient in the insulation of each conductor is the same, the maximum potential gradient is higher with the smaller diameter, which should therefore break down at a lower voltage.

For the same voltage and temperature gradient in the insulation the space factor of a concentric-conductor bar is 30 % better than that of a normal conductor with graded insulation, and 70 % better than that of a fully insulated conductor.

Probably the main reason why corona seldom leads to the breakdown of micanite insulation is that ionized air has practically no effect upon mica. It also has been shown* that the increase in voltage stress in a small air bubble in solid insulation is little greater than that in the insulation itself, instead of 3 or 4 times as would be expected from the relative values of the specific inductive capacity.

The circulating current of 25 % which was obtained by Prof. Marchant is unusually high; the value normally obtained is too small to affect protective apparatus.

It will be generally agreed that resistance earthing is safer for all types of equipment than the arc-extinction coil, but the advantage of the latter in dealing with flashovers without disconnection of a line may lead to its wider application.

In reply to Mr. Juhlin, it seems clear from the evidence that the failure referred to on page 347 was initiated at the same time as the breakdown of the main step-up transformer. In my opinion the alternator was isolated owing to the inadvertent operation of the protective apparatus caused by the fault current. Under these conditions the neutral would also be left open, and the conditions favourable to neutral inversion were again present.

The flashovers across the terminals at Salt River were indirectly due to neutral inversion, as is explained in the paper. The atmospheric conditions at Salt River are exceptional and no similar difficulties have been experienced elsewhere.

The concentric-conductor construction has the advantage of reducing the potential gradients in the end windings as well as in the conductor insulation. With this type of winding the problem of the insulation of the end connections is similar to that which arises in connection with an ordinary low-voltage design. The insulation of the outer conductor to the core is the same, while between sections the insulation is greater as both conductors can be fully insulated.

The end windings are impregnated with a varnish having a bituminous base, and numerous tests on insulated joints showed that the impregnation is effective. The problem of impregnating windings on site will not be found insuperable should it ever be necessary to tackle it

I would inform Mr. Pryce-Jones that the commutation of 3 000-r.p.m. exciters has been satisfactory for a number of years and no difficulties are experienced provided that the mechanical construction and manufacture of the commutator is sound. I agree with his views on pressure testing, and I consider, as stated in my reply to Mr. Richardson, that more information is obtained from routine insulation-resistance measurements than from loss tests made by means of the Schering bridge. The switchgear referred to on page 351 is of the metalclad type, but even if it is necessary to earth the voltage-transformer neutral there are, as enumerated in the paper, several simple and effective safeguards against neutral inversion.

In reply to Mr. Macfarlane, the concentric-conductor winding has up to the present only been employed for turbo-type alternators.

The use of hydrogen under pressure for the ventilation of machine windings has been proposed a number of times in the past. It would have the advantage Mr. Macfarlane mentions, and its application has been prevented mainly by practical difficulties of construction. Further proposals have been made recently in America to use hydrogen under pressure for the ventilation of turbo-type alternators.* Tests have been made on a synchronous condenser cooled by hydrogen under a pressure of 15 lb. per sq. in.†

The copper sleeve and loop in Fig. 3 mentioned by Mr. Kilner are both integral parts of the end connection. The insulation of the joints may at first sight appear complicated but in practice a technique of insulating the joints has been developed which is relatively simple. The manufacture of the bush in a special mould ensures that its dimensions are accurate. No difficulty is therefore experienced in fitting it closely over the insulating tube and into the eye of the end connection.

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* R. Bruce: "Air Spaces in Solid Insulation," *Heaton Works Journal*, 1939, 3, No. 15.

* D. S. Snell: "The Hydrogen-cooled Turbine Generator," *Electrical Engineering* (Transactions Section), 1940, 59, p. 35.

† P. Sporn and F. M. Porter: "Application and Operation Experience with Hydrogen-cooled Synchronous Condensers and Alternators," American I.E.E. Winter Convention, January, 1940.

I agree with Mr. Kilner that the earthing of the alternator neutral by means of a moderately high resistance would be advantageous under some conditions provided that no difficulties with harmonic circulating currents or protective apparatus were introduced. The practice is of particular advantage in limiting surge voltages in windings with graded insulation where the low-voltage conductors are not adequately insulated.

Inter-turn protection is not necessarily superfluous for low-voltage machines. If the between-turn insulation were equivalent to the main insulation to earth it would be only logical to provide the same degree of protection against failure. A higher level of insulation between turns is obtained only at the expense of valuable space. This disadvantage becomes more evident in high-voltage machines, particularly where every turn is fully insulated.

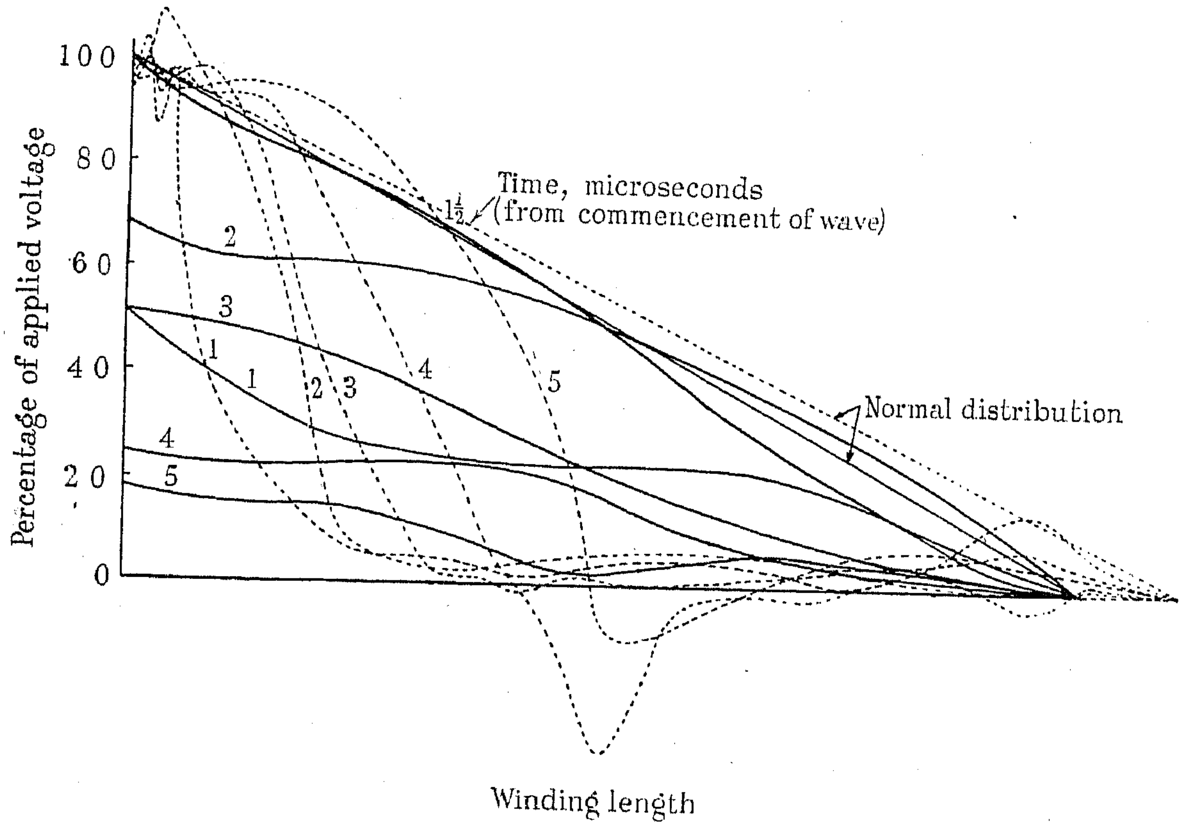

Fig. C.—Impulse-voltage distribution in (a) concentric-conductor h.v. alternator winding, (b) transformer winding.

(a) ——
(b) - - - -

The conclusions reached in the paper were only arrived at after very careful study of the evidence, and it is gratifying to know that Mr. Winfield is in general agreement with them. He draws attention to the possibility of impaired insulation in the Salt River alternators being the root cause of the difficulties. Contrary to this suggestion is the evidence that no inherent weakness or deterioration was found in the windings at the end of the alternator not damaged by the breakdown of the lead extensions. After the removal of the damaged end-connections the complete windings withstood a graded pressure test of 60 kV.

I agree with Mr. Winfield that once the possibility of neutral inversion is recognized, it can be dealt with effectively in a relatively simple manner. Failing the isolation of the voltage-transformer neutral, one or more of the methods discussed in the paper should be satisfactory. Some of these methods have not yet been proven in practice, and as an additional safeguard it does not seem unreasonable to earth the alternator neutral during the danger period. I agree that the complication is undesirable, and after a little experience it should be possible safely to dispense with this extra precaution.

Mr. Winfield's observations on 3-phase neutral earthing switches, and on ozone, are of interest. While it is true that the voltage between turns in the concentric-conductor winding is equal to one-third of the phase voltage, the operating voltages are no greater than in a low-voltage design. The total number of conductors is the same as in a high-voltage machine of "normal design," and therefore, as explained in detail in an earlier paper, the concentric-conductor winding has considerable advantages. The initial distribution of surge voltages in the concentric-conductor winding is shown in Fig. C, and the results of more recent tests confirming the equally favourable distribution of oscillations due to long-tail waves in this type of winding are briefly referred to in my reply to Dr. Kahn.

It is satisfactory to know that Mr. Winfield's experience with 33-kV generation leads him to contemplate the possibilities of alternators designed for 66-kV generation. Investigations and tests on designs based upon the concentric-conductor principle are in progress at the present time, and the 66-kV generator appears not far-distant.

Mr. Leyburn should consult my reply to Mr. Carter for a discussion of the use of the term "neutral inversion." The phenomenon of neutral inversion has occurred in only two power stations where high-voltage alternators are installed, and, while there is no doubt that it could be reproduced in both, it will be appreciated that there would be difficulties and a slight element of risk in making the attempt, even if precautions were taken to limit the voltage generated.

Experiments have been made on a 5 000-kVA turbo-type alternator using spark gaps to prevent excessive over-voltages, and some details of these tests are given in Mr. Easton's contribution to the discussion.

It was found that the first stage of neutral inversion in the form of voltage fluctuations appears at a density in the voltage transformers as low as 7 500 lines per cm^2. The second stage begins at a density of 11 500 lines per cm^2, when the gaps flash-over intermittently, and the third at a slightly higher density with continuous flashing-over of the spark gaps. The transition between the second and third stages is spontaneous and rapid. In these tests a balanced arrangement of three single-phase transformers was used, whereas in the stations mentioned the arrangements were unsymmetrical, thus lowering the density at which neutral inversion occurs and promoting the building-up process.

The large number of methods available for preventing neutral inversion, most of which are discussed in the paper, should be sufficient evidence that the problem is not a difficult one. The advantages of phase-isolated switchgear are fully appreciated. Mr. Leyburn considers that phase isolation of associated voltage transformers necessitating an earthed neutral point is essential, but Mr. Gregory does not appear to support this view. I agree that the preventive measures favoured by Mr. Leyburn should be effective.

My views on the additional precaution of earthing the alternator neutral are given in my reply to Mr. Winfield.

Both sphere and paper gaps are successfully used in alternator neutrals, and if set sufficiently high should not cause difficulty by breaking down every time an earth fault occurs on the system.

Earthing transformers are expensive, and a comparatively high earthing resistance appears to be a satisfactory and less costly alternative.

The scheme of inter-turn protection described by Mr. Leyburn is of much interest, and should be effective.

Mr. Easton's observations on neutral inversion are generally in line with those expressed in the paper, and the detail he gives of the experiments which have been made are of much interest.

I strongly support Mr. Mitchell's views on neutral inversion, and particularly his statement that it is rare and does not merit the undue prominence given to it in the discussion.

The calculations of the over-voltages caused by neutral inversion were based on the stored electromagnetic energy in the voltage transformers, on the assumption that resonance occurs at the fundamental frequency, and a suitable allowance was made for the effect of harmonics caused by saturation. A graphical method is given in an article by Dr. J. T. Hattingh.*

I agree with Mr. Mitchell that additional protection is only justified if the cost is reasonable in relation to the incidence of faults.

In reply to Mr. Macdonald, the power factor of conductor insulation is measured by means of the Schering bridge. The actual value, which is of the order of 0·02, depends upon a large number of factors and it is not possible to give a limiting value which would be universally applicable. Schering-bridge tests are made on individual conductor bars and on all completed machines, and a considerable amount of information has been gained from them. Up to the present it has not been found that power-factor measurements on machines are of sufficient value to justify routine measurements being made on site. On the other hand, valuable information is obtained from routine insulation-resistance testing, and this point is discussed by Mr. Richardson.

I agree with Mr. Kennedy that neutral inversion is not a common phenomenon, and I do not consider that the treatment and amount of space devoted to it in the paper suggest otherwise. I agree that, of the conditions which he quotes as being essential for neutral inversion, (1) and (4) must be fulfilled, but according to the tests described by Mr. Easton (2) and (3) do not appear to be essential.

The capacitance of the windings of the two Salt River alternators is 0·07 μF per phase, and the saturation curve of the voltage transformers is shown in Fig. D. From these particulars the resonance voltage can readily be calculated using the methods indicated in Items (7) to (11) of the Bibliography.

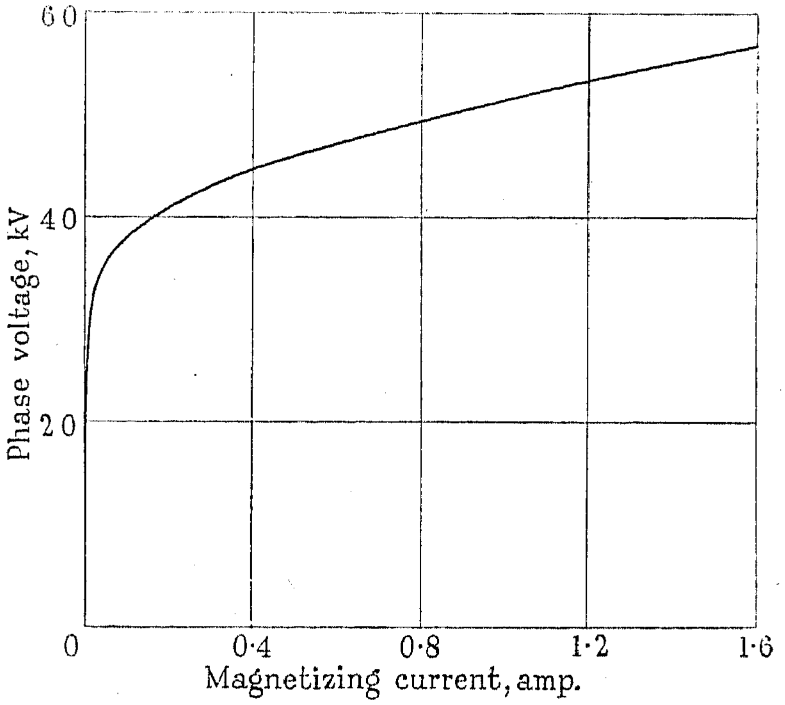

Fig. D.—Magnetization curve for 33-kV instrument (voltage transformer).

The flashover voltage deduced from the path of the fault was determined by careful tests on a full-size replica of the end connections and supports. In the first fault, where the discharge took place through air, there was no "creepage" across any part of the surface of the insulation.

Mr. Kennedy's suggestion that the flashover across the lead extension insulators at Salt River was due to a static charge is untenable, as the alternators are permanently earthed, even when disconnected from the system, through the windings of the voltage transformers.

As previously explained, the constants of the two circuits in which neutral inversion was experienced were such that it occurred in its most intense form, and the build-up to this stage was extremely rapid. The symptoms of neutral inversion which he mentions would therefore not be evident. Mr. Kennedy appears to have misread the paper, as the parts of the windings affected were not all operating at a voltage of 6·5 kV to earth and the faults were not confined to one phase or one part of the winding.

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* *Electrician*, 1935, **114**, p. 825.

All reputable manufacturers of important electrical apparatus take great care in regard to the insulation of their products. The improvements described in the paper are part of normal development and progress, in which full advantage has been taken of the experiences with the failure of one joint at Swansea and two outer-conductor insulating tubes on one alternator at Brimsdown.

Mr. Kennedy questions the existence of neutral inversion in the experiences reviewed in the paper, and his attack upon the conclusions reached appears to be based upon an entirely unfounded fear that their acceptance means in the future the isolation of the neutral points of voltage transformers, with the consequent rejection of phase-isolated switchgear and its unquestioned advantages. His apprehension is quite unjustifiable, and indeed in Mr. Gregory's view phase-isolated switchgear and the isolation of voltage-transformer neutrals are not incompatible.

Mr. Burgess's questions are answered in the first two paragraphs of Section (1) of Part 3 of the paper. The individual fibres of glass-silk yarn cannot absorb moisture, although this may collect on the surface of the fibres of the woven material. It is satisfactory to have Mr. Burgess's emphatic endorsement of the soundness of the principle of impregnation for all air-cooled plant.

The use of spark gaps for earthing is dealt with in my reply to Mr. Leyburn.

Mr. Gregory expresses very clearly the reasons and advantages of high generating and switching voltages. He presumably only recommends generating and switching at the transmission voltage where the bulk of the load has to be transmitted an appreciable distance. When a large proportion of the load is to be absorbed within a short distance it would appear more economical to generate at the highest distribution voltage or secondary transmission voltage and to provide a smaller step-up transformer for the export load.

While, as stated in my reply to Mr. Winfield, 66-kV alternators are becoming more feasible, it seems too early to express any opinion on the possibility of constructing 132-kV machines.

Mr. Gregory's views on phase-isolated voltage transformers are of much interest.

I agree with Mr. Carter that the term "potential instability" would accurately describe the phenomenon referred to as "neutral inversion." There are, however, many forms of potential instability and there are advantages in distinguishing between them. Neutral inversion is a peculiar form of potential instability, and its name was given to it by one of the earlier investigators of the phenomenon. The term is not inappropriate, as during the state of neutral inversion the neutral of the apparatus is raised to a high potential above earth and may thus be said to be "inverted" above the neutral point of the voltage transformers responsible for the high resonance potentials.

THE DRYING PROCESS IN PAPER, AS DETERMINED BY ELECTRICAL METHODS*

By C. G. GARTON, Associate Member.

(*Paper first received* 13*th April, and in revised form* 18*th July*, 1939.)

SUMMARY

The nature of the drying process in paper, at two temperatures and various ambient pressures, has been investigated. Apparatus has been developed, and is described, which permits the drying process to be investigated at high vacua, and which is sufficiently sensitive to measure the electrical changes due to a water content of the order of 0·05 % of the weight of cellulose present. A number of theoretical conclusions has been derived from the experimental data, and these are summarized at the end of the paper.

CONTENTS

(1) Introduction.

(2) Apparatus, and Methods of Test.

(3) Experimental Results.

(4) Discussion of Results.
  (*a*) The concept of "residual moisture."
  (*b*) The electrical characteristics of completely dry paper.
  (*c*) The electrical characteristics of water adsorbed on cellulose.

(5) Conclusions.

(6) References.
  Appendix. Drying Time as a Function of Shape of Electrode System.

(1) INTRODUCTION

The importance of moisture in paper insulation led to the present investigation, which deals with two main aspects of the problem. The first is the relation between electrical properties and small amounts of moisture in paper, with the particular object of deciding the completeness or otherwise of drying processes at various temperatures and air pressures. The second is the reliability of moisture determination by electrical methods, especially the method of capacitance measurement at two frequencies. These matters, apart from their intrinsic interest, have acquired some prominence due to recent work of investigators in America,^{3} and it was desired to compare the results obtained in the present research with certain of their conclusions, particularly the conception of "residual moisture."

Subsidiary objects were to find the actual quantity of water corresponding to the observed electrical changes, and to account theoretically for the observed contribution of the water to the capacitance and losses of the paper.

Three types of paper were tested, as follows:—

Sample No. 350, described as an "all-rag cotton paper."
Sample No. 358, described as a "pure white cotton paper."
Sample No. 822, described as a paper made from a special wood pulp supplied by the Brown Paper Co. (U.S.A.).

No analyses were made of these papers, but an indication of the constituents of similar papers may be obtained from Reference (1). Unfortunately, neither the papers tested, nor those analysed in the reference quoted, are described with sufficient precision to allow of exact comparison. It can be said, however, that the probable content of alpha-cellulose for all three papers lies in the region of 90 % to 95 %.

(2) APPARATUS, AND METHODS OF TEST

The samples were in the form of single circular sheets. Measurements of thickness and all electrical measurements were made under a pressure of 2 lb. per sq. in. Table 1 gives details of the samples.

Table 1

Sample No.	Diameter	Active diameter	Thickness	Dry weight	Apparent density	κ, 50 c./s. to 50 kc./s. (approx.)
	cm.	cm.	cm.	g.	g. per cm^3	
350	8·25	7·6	0·0122	0·290	0·445	1·63
358	8·9	7·6	0·0147	0·425	0·465	1·78
822	8·9	7·6	0·0211	0·775	0·59	2·05

It would have been preferable to use several sheets in each sample, but the thickness of the paper made this impracticable as it would have given an inconveniently small capacitance, or large diameter, of the sample.

The electrodes consisted of accurately flat polished brass plates, 6 mm. thick, the low-voltage electrode being 7·6 cm. in diameter, and surrounded by a guard ring with a separating gap of 0·8 mm. A sheet of pure soft tin, 1 mil in thickness, was placed between electrodes and paper on each side. A pressure of 2 lb. per sq. in. was maintained on the active area of the sample by lead weights, to a total of 14·7 lb., resting on the top electrode, but separated from it by three glass spacers. The guard ring was not subjected to pressure other than that due to its own weight.

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* Official communication (Ref. A/T72) from the British Electrical and Allied Industries Research Association.

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The electrode system was mounted within a brass vacuum chamber, with inlet and outlet tubes for the circulation of dry air, and with metal-to-glass vacuum seals carrying the connections to the electrodes. Gasket joints of organic material, undesirable at high temperatures, were avoided by closing the lid of the chamber on to a soft aluminium ring, 1 mm. thick, compressed between a knife-edge and a flat surface by a ring of eighteen $\frac{3}{8}$-in. Whitworth bolts. This somewhat unconventional seal proved entirely satisfactory, holding vacua of the order of 10^{-3} mm. Hg without apparent leakage, and without the use of any non-metallic material. The bolts should be tightened only very moderately, otherwise the ring is cut through.

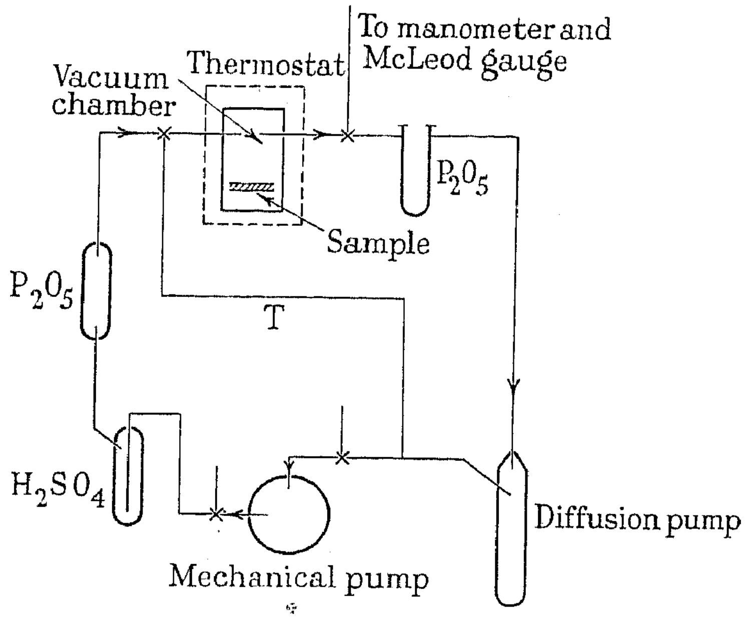

Fig. 1.—Vacuum circuit.

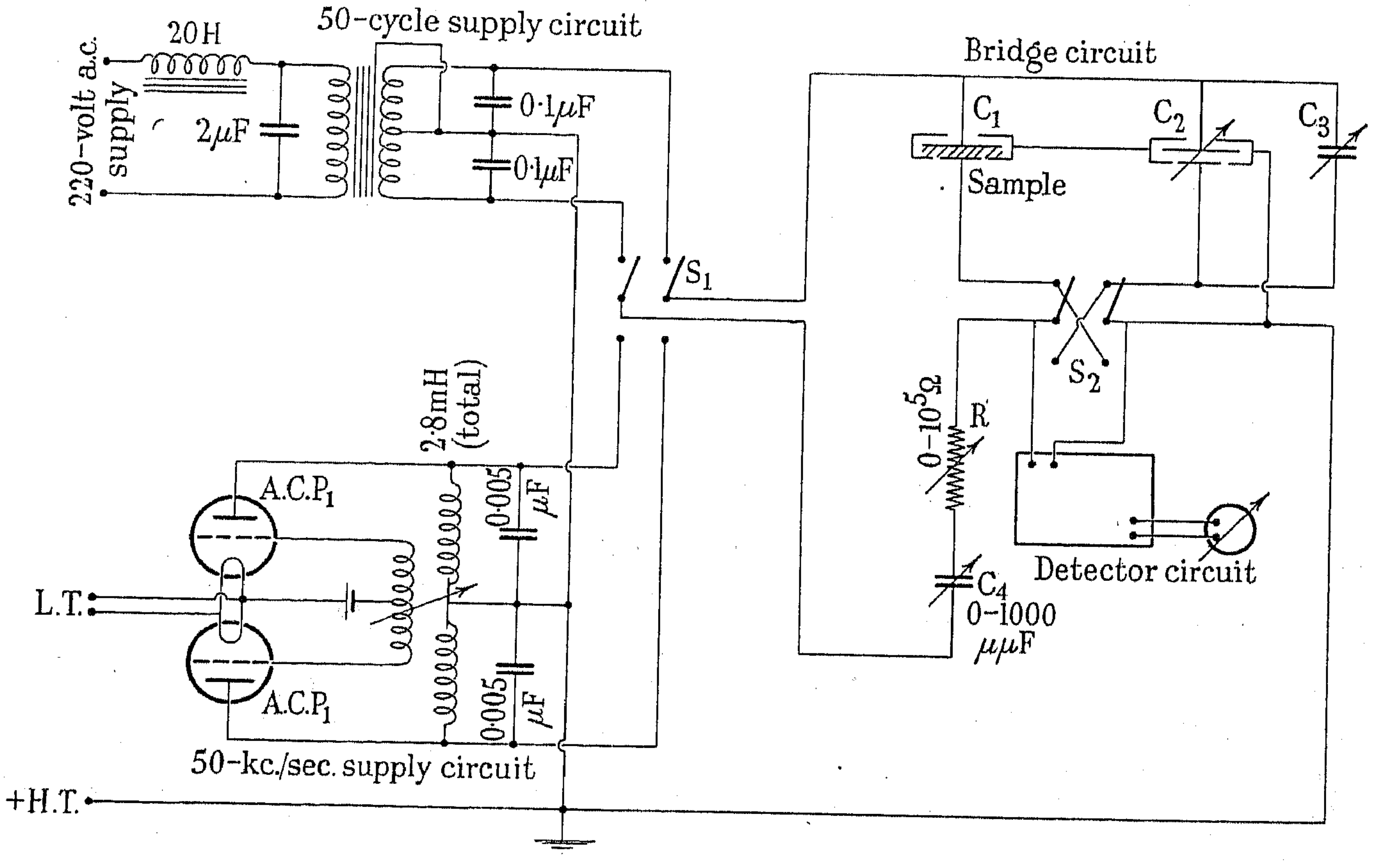

Fig. 2.—Supply and bridge circuits.

The vacuum chamber was mounted within a thermostat with automatic temperature control. A diagram of the vacuum system is given in Fig. 1. A mechanical pump and a mercury diffusion pump in series allowed any pressure between atmospheric and 10^{-4} mm. Hg to be obtained by operating one or both of them. The outlet of the mechanical pump was enclosed, and air emerging from the pump was led back, via H_2SO_4 and P_2O_5 tubes, into the vacuum chamber, so that the same air, dried *en route*, could be repeatedly circulated in the system. A second P_2O_5 tube, in the outlet from the chamber, collected water released from the sample, and could be removed from the system for weighing, without breaking the vacuum. A further return tube (T in the diagram) permitted circulation at high vacua through the diffusion pump only. This tube, though provided, was unnecessary, as intermediate pressures were not used, and at high vacua the diffusion of water vapour was sufficiently rapid without intentional circulation.

The measuring circuit used, shown in Fig. 2, is a form of substitution bridge, but differs from a true bridge in that two arms consist of transformer windings in which the bridge voltage is generated. The circuit has some analogy with the " inductive ratio arm " bridges described by Hague,[2] and consists of four main parts, as follows:—

(*a*) The 50-cycle supply circuit consists of a shielded transformer, fed from the mains through a choke, and shunted on both primary and secondary sides by condensers. The purpose of these is to eliminate harmonics and mains disturbances.

(*b*) The 50-kc./s. supply circuit consists of a 50-kc./s. " push-pull " oscillatory circuit. The design of the oscillatory coil is of some importance, as the potential of the centre tap with respect to the ends must remain constant for small changes of capacitance in the bridge circuit. This is achieved by very close inductive coupling between the two halves of the coil.

(*c*) The bridge proper consists of two arms, one containing a variable resistance and a variable condenser (R and C_4, see Fig. 2), and the other consisting alternatively of the condenser formed by the sample under test (C_1) or a loss-free variable air condenser with vernier adjustment (C_2 and C_3). Either C_1 or C_2 can be thrown into the circuit by the switch S_2, which at the same time earths the condenser not in use. The condenser C_4 need not be calibrated, nor need it be loss-free, provided its losses are neither large nor variable.

(*d*) The detector circuit, connected from the centre point of either supply circuit to the centre point of the two bridge arms, consists of a valve voltmeter having one stage of amplification.

With switch S_1 set to the desired frequency supply, and switch S_2 set to include the sample C_1 in the bridge, balance is obtained by adjustment of R and C_4. Let the reading of R be R_0. S_2 is then reversed, substituting the standard condenser for the sample, and balance is obtained by adjustment of C_2, C_3, and R. Let the combined capacitances of C_2 and C_3 be C, and the value of R be R_1. Then, provided that the centre tapping of the supply circuit is symmetrical with regard to the total voltage (a condition readily obtainable to a sufficient accuracy),

$$C_1 = \frac{C}{1 + \tan^2 \delta}$$

and

$$\tan \delta = \omega C(R_1 - R_0)$$

If the tapping be not symmetrical, no error is caused in the value of capacitance but a percentage error in tan δ results, equal to the percentage lack of symmetry of the tapping.

The bridge is extremely sensitive to stray capacitances, and all components and leads were thoroughly screened, although this, for simplicity, is not fully shown in Fig. 2. All stray inductances were kept to a minimum by appropriate grouping of the leads. Both bridge and supply circuits were in separate iron boxes, and were removed some distance from one another to avoid magnetic induction.

The effect of capacitance to earth from the junction of R and C_4 can be eliminated only by double screening, which was not employed. The effect is to render the apparent loss angle too small in the ratio $C_4/(C_4 + C_e)$, where C_e is the capacitance to earth. Since in the present case C_4 was about 500 $\mu\mu$F, the effect was small and an approximate correction easily made.

The overall accuracy of the bridge was checked by substituting three very small mica spacers for the paper sample, thus converting the electrodes into a practically loss-free air condenser. The apparent change of capacitance with frequency was $0 \cdot 1$ $\mu\mu$F, and there may, therefore, be a systematic error not greater than this in the results. The loss angle was correctly indicated as $0 \cdot 0000$. The sensitivity of the bridge was $\pm\ 0 \cdot 03$ $\mu\mu$F in capacitance, and $\pm\ 0 \cdot 00002°$ in phase angle, but there were probably errors present of the order of 2 or 3 times these limits. The measurement of the absolute value of capacitance, as distinct from small changes in it, was limited to about $\pm\ 1 \cdot 0$ $\mu\mu$F, but this is of no importance for these tests.

The unconventional nature of the bridge requires some explanation. A substitution type of bridge was essential to permit very accurate comparison of capacitance changes over a frequency range of 1 000 to 1. The high sensitivity required with a low voltage suggests an equal-arm bridge rather than a circuit of the Schering-bridge type. This leads to consideration of the Fleming–Dyke bridge of four condensers. Owing to the large frequency range, the ratio-arm condensers of such a bridge would require two widely different values at the two frequencies, thus necessitating a further four accurate components for the bridge circuit. Consideration of a substitution type of bridge will show, however, that measurement of capacitance does not depend at all, and phase angle only slightly, upon exact similarity of the ratio arms. In fact, the only function of the ratio arms is to provide a point of reference for the measurement of the detector voltage, and provided the potential of this point is not changed by the substitution it is immaterial, within limits, what the potential of the point may be. Such a point is very easily obtainable by a centre tap in a suitable supply circuit, thus rendering the ratio arms superfluous, simplifying the circuit, and giving considerable economy of apparatus. The general principle is not new, as may be seen from Reference (2). Considerable experience with the bridge described has shown it to be both reliable and accurate.

Temperature variations of the sample were limited, in the first tests, to $\pm\ 0 \cdot 5$ deg. C., but this caused irregularities in the results, and in the later tests an accuracy of $\pm\ 0 \cdot 1$ deg. C. was aimed at, but not always maintained. Most of the irregularities in the results were related to slight changes of temperature.

The quantity of water released from the sample could not be measured with much accuracy, since it was always small, of the order of 10 mg. during the entire run and much less than this in the final stages of drying. Under reduced pressure, and especially at the lowest pressure of 10^{-3} mm. Hg, water was released from the walls of the vacuum chamber. For this reason, all the water determinations at high vacua are believed to be spurious, and are not recorded. The readings at atmospheric pressure appear to be free from this error. At the beginning of a run, the vacuum chamber is filled with water vapour released by the sample. This water, if not removed, would figure in the water determination, although, having left the sample, it does not affect the electrical readings. At atmospheric pressure, the error may be very large, for which reason the apparatus was given a brief preliminary evacuation to about 1 mm. Hg before beginning a run. The error is thus much reduced, but not entirely eliminated. Its precise value is difficult to estimate, but is of the order of a few per cent.

The samples were placed in the vacuum chamber without preliminary conditioning, and the temperature brought to constancy at the desired value. The chamber was then full of wet air. This was removed by evacuation, during which the water remaining in the sample decreased very rapidly. When it had fallen to a suitable value, dry air was admitted to the chamber and a set of electrical readings taken. A weighed P_2O_5 tube was then inserted, and circulation of dry air started, at the rate of a few millilitres per minute. The rate of drying does not depend upon the rate of circulation, unless this is very slow. A run thus started was continued without interruption until its completion, in some cases over as long a period as 6 days; readings of capacitance and loss angle being taken at suitable intervals. On completion of a run at atmospheric pressure, as indicated by constancy of the electrical readings, the diffusion pump was started, and the run continued at the highest attainable vacuum, in these tests between $0 \cdot 5$ and $0 \cdot 8 \times 10^{-3}$ mm. Hg.

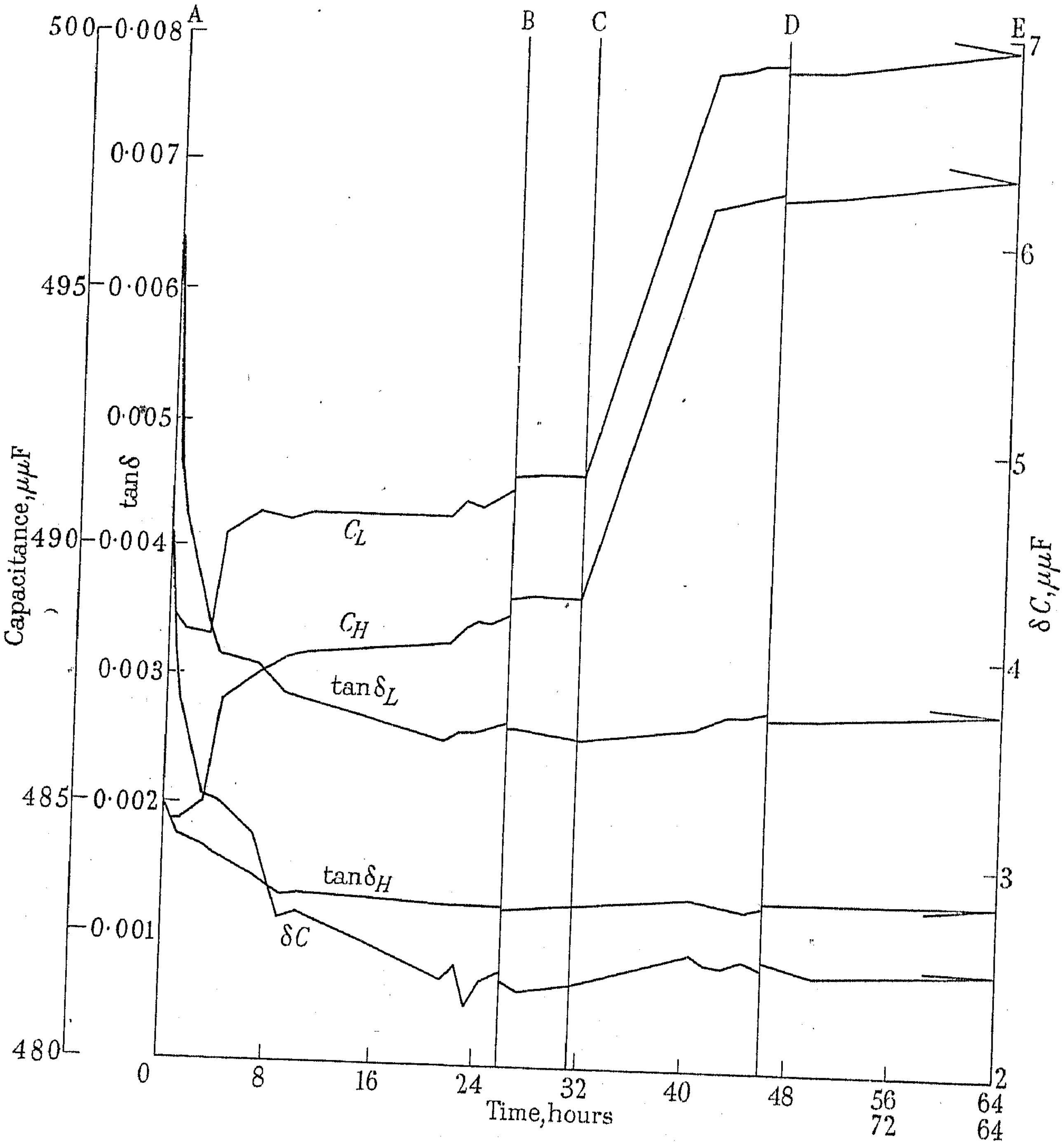

Fig. 3.—Sample No. 538 at 100° C.: tests at various pressures.
The vertical lettered lines indicate the times at which the ambient pressure was altered, as follows:—
Interval A—B pressure 755 mm. Hg.
B—C pressure 2 mm. Hg.
C—D pressure 0·1 mm. Hg.
D—E pressure $0 \cdot 5 \times 10^{-3}$ mm. Hg.

(3) EXPERIMENTAL RESULTS

In all, ten runs were made on the three samples. The conditions of the runs, together with the initial and final values of capacitance and loss angle, are given in Table 2. The detailed results of four runs at 100° C. are given in Fig. 3, and of two runs on another sample at 60° C. are given in Fig. 4. The results of the remaining four runs at 60° C., for which detailed results are not shown, were very similar to those given in the curves of Fig. 4.

In the curves, the symbol δC denotes the change in capacitance, in μμF, between the value measured at 50 c./s. and that at 50 kc./s.

In run No. 9, an attempt was made to measure the quantity of water released, at intervals during the run. The results of this are shown in Fig. 4 by the curve labelled W.

After the completion of run No. 10, on sample No. 350, and while the sample was still in the dry state, readings were taken of the capacitance and loss angle at 50 c./s. and 50 kc./s. over the temperature range from 20° to 100° C. These results are shown in Fig. 5. The

Table 2

Sample No.	Run No.	Temperature	Pressure	Duration	W	C_{L0}	C_{H0}	C_L	C_H	tan δ_{L0}	tan δ_{H_0}	tan δ_L	tan δ_H	Fig. No.
		° C.	mm. of Hg	hours	mg.	μμF	μμF	μμF	μμF					
358	1	100	755	26	14·5	490·1	484·97	491·2	488·75	0·0062	0·00205	0·00267	0·00124	3
358	2	100	2·0	5½	—	491·2	488·75	491·5	489·1	0·00267	0·00124	0·00253	0·00125	3
358	3	100	0·1	14½	—	491·5	489·1	499·5	497·0	0·00253	0·00125	0·00278	0·00127	3
358	4	100	$0 \cdot 4 \times 10^{-3}$	23½	—	499·5	497·0	500·05	497·55	0·00278	0·00127	0·00283	0·00128	3
358	5	60	755	74	8·5	495·45	491·05	491·8	489·3	0·00145	0·00338	0·00090	0·00278	—
358	6	60	$0 \cdot 5 \times 10^{-3}$	19½	—	491·8	489·3	491·6	489·3	0·00090	0·00278	0·00080	0·00274	—
822	7	60	755	139	31·0	404·3	397·2	390·97	388·4	0·00580	0·00491	0·00116	0·00315	—
822	8	60	$0 \cdot 8 \times 10^{-3}$	22	—	390·97	388·4	390·9	388·73	0·00116	0·00315	0·00097	0·00306	—
350	9	60	755	122½	11·0	542·5	536·33	539·27	536·9	0·00347	0·00347	0·00094	0·00216	4
350	10	60	$0 \cdot 8 \times 10^{-3}$	21	—	539·27	536·9	539·7	537·57	0·00094	0·00216	0·00083	0·00217	4

The following is a key to the column headings of Table 2:—

C_{L0} = capacitance, in μμF, at 50 c./s., of a sample at start of run.
C_{H0} = capacitance, in μμF, at 50 kc./s., of a sample at start of run.
C_L = capacitance, in μμF, at 50 c./s., of a sample at end of run.
C_H = capacitance, in μμF, at 50 kc./s., of a sample at end of run.

The suffixes for tan δ have analogous meanings.

W is the total quantity of water, in milligrammes, extracted from the sample during the run. To obtain the quantity of water contributing to the electrical changes, this must be multiplied by the ratio (active diameter/total diameter)^2 of the sample, from Table 1.

capacitance readings have been corrected for thermal expansion of the electrodes, but not for that of the paper, which is probably very small, provided that the paper is really dry.

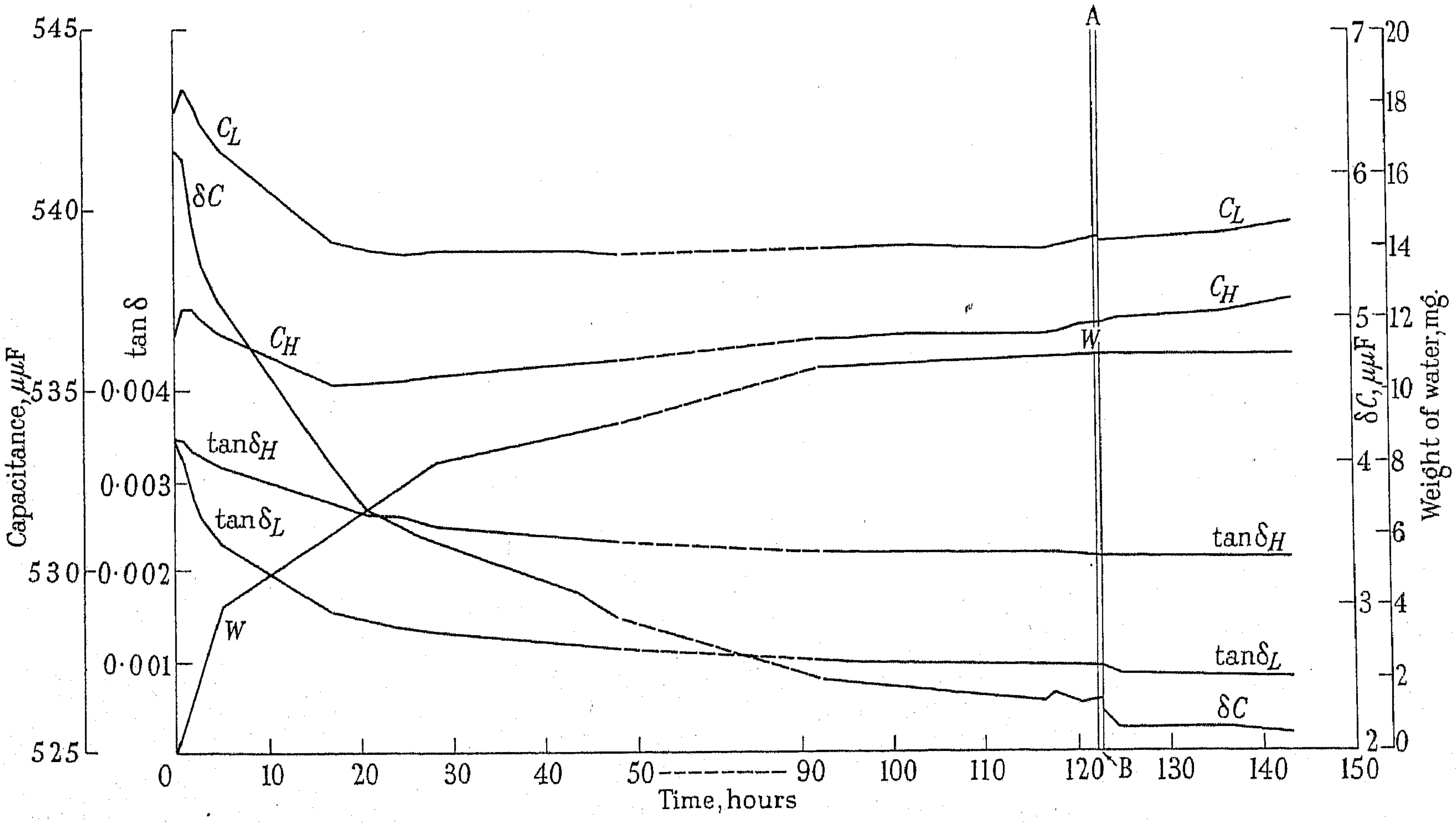

Fig. 4.—Sample No. 350: tests at atmospheric pressure and $0 \cdot 8 \times 10^{-3}$ mm.

The vertical line AB indicates the time at which the ambient pressure was decreased from 755 mm. Hg to $0 \cdot 8 \times 10^{-3}$ mm. Hg.

(4) DISCUSSION OF RESULTS

(a) The Concept of "Residual Moisture"

Upon the completion of runs Nos. 1 to 4 inclusive upon the first sample (see Fig. 3) it became evident that the conception of "residual moisture," in the sense of a moisture content capable of extraction only at pressures lower than atmospheric, is not valid if the ambient atmosphere be completely dry, since the removal of water proceeds to completion, given sufficient time, even at atmospheric pressure, as shown by the loss-angle and the δC curves of Fig. 3. The only effect of reduced pressure is greatly to accelerate the process. Further runs were therefore made at two pressures only: atmospheric, and the lowest obtainable with the available apparatus, about 10^{-3} mm. Hg.

The next two runs, Nos. 5 and 6, showed that the same conclusion holds also at 60° C., but with a greatly increased time of drying. (For typical results at this temperature, see Fig. 4.) No further tests, therefore, were made at 100° C., since if complete drying be possible at 60° C. it is, *a fortiori*, possible at 100° C. Runs Nos. 7 to 10 inclusive merely confirmed the conclusions already reached, and extended them to the other grades of paper.

The criterion of "complete" removal of water was taken to be constancy of electrical characteristics during prolonged heating at high vacuum, together with a very small or zero change in the characteristics when the ambient pressure was reduced from atmospheric to 10^{-3} mm. Hg or less—a pressure ratio of about 1 million to 1. The greatest decrease in loss angle in any of the ten runs, due to this reduction of pressure, was 0·0002, and this in one case only. The greatest decrease in δC (also a measure of the dryness) was 0·1 %, again in one case only. Still smaller differences could have been achieved by continuing the drying process at atmospheric pressure for some days longer, since the results at 60° C. were not quite constant even after a period, in one case (run No. 7), of 6 days' drying. The point, however, seemed sufficiently demonstrated without further expenditure of time. It is considered that the absence of appreciable change in the electrical characteristics when the ambient pressure is varied by a factor of 1 million times is convincing evidence that the paper is completely dry, and that it can reach this condition at atmospheric pressure, provided that the ambient air be also completely dry.

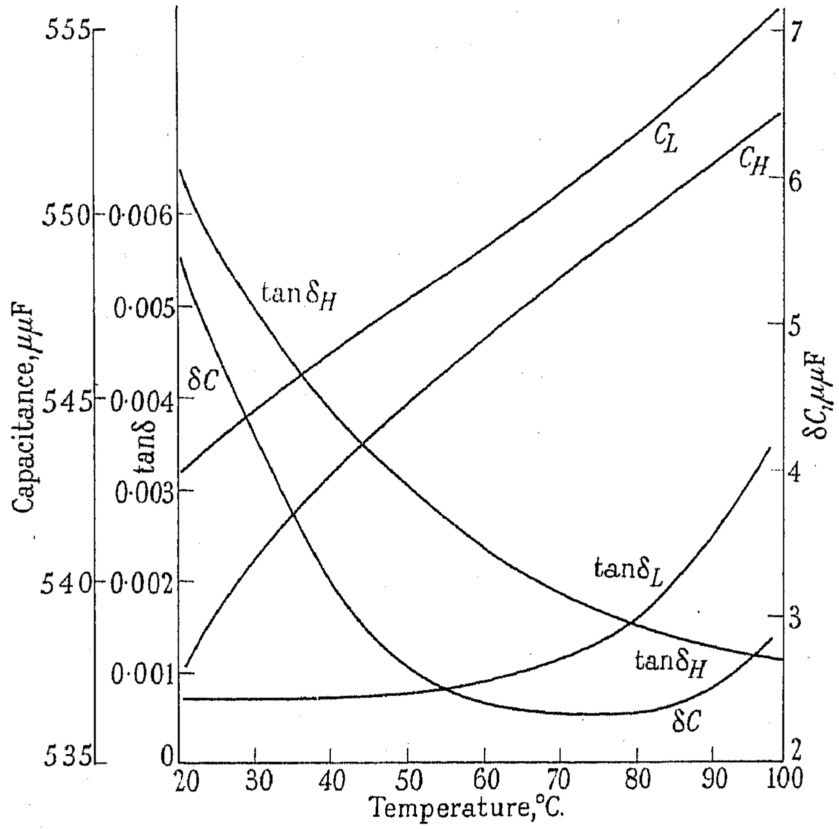

Fig. 5.—Sample No. 350: variation of characteristics with temperature.

This conclusion can be reconciled with that reached by American investigators[3] only on the assumption that the ambient atmosphere in their work was not free from water vapour. Obviously, if a partial pressure of water vapour exist around the sample, equilibrium will ultimately be established between this and the water in the sample, and drying will then cease, although a dry atmosphere at the same pressure would, as shown by the present work, carry the drying of the sample to completion. In addition to Reference (3), the original papers (References 4 and 5) may be consulted, but the details given do not permit an estimate of the water vapour pressure to be made.

A further possible cause of difference between the two investigations is the large size of the American samples (180 cm³ of paper, against 1·3 cm³ in our case) and their unfavourable shape, which took the form of long thin cylinders. The Appendix shows that a cylinder of the dimensions used would possess a drying "time-constant" 125 times greater than the constant for the samples used in the present work, on the (incorrect) assumption that the water could escape only from the ends of the cylinder. The American electrodes, however, are stated to have been pierced with "small holes at a spacing of 2·54 cm." The effect of these is difficult to estimate, since their size is unknown, but if the whole surface were covered with holes at the stated spacing the time-constant would be very greatly decreased. Without more precise information it is not possible to state which of the suggested causes of difference is the more important, but the present work indicates that, whatever be the cause, the equilibria reached in the American work were due to the experimental conditions, and not to an inherent property of the paper.

(b) The Electrical Characteristics of Completely Dry Paper

In discussing the results, it is necessary to distinguish carefully between three different capacitance-changes, namely

(i) δC, the difference between the capacitance at 50 c./s. and that at 50 kc./s., for any given condition of the sample.

(ii) δC_0, the value of δC when the sample is in the completely dry state.

(iii) ΔC, the change in the capacitance, at one given frequency, from the initial condition to the end of a run, due to loss of moisture.

δC and δC_0 can be measured with considerable accuracy, but ΔC is subject to large errors due to gradual compression of the sample, which produces a spurious apparent increase of capacitance with drying. This increase is accelerated by rise of temperature and particularly by decrease of gas pressure (see, for example, Fig. 3, the case in which the pressure was first reduced to 0·1 mm. Hg). In two cases only, runs Nos. 5 and 7, was it possible to obtain approximately correct values of ΔC, and even in these cases the possible error is unknown. To obtain accurate values would necessitate stabilizing the mechanical state of the sample by long preliminary drying at high temperature and high vacuum, followed by re-absorption of moisture and re-drying to obtain readings.

The values of δC_0 and tan δ (dry) for the three types of paper are given in Table 3. In addition, the values of δC_0 and tan δ (dry) for sample No. 350 are shown in Fig. 5, for a range of 20° to 100° C.

From these results it is evident that neither δC_0 nor tan δ becomes zero in the dry state.

This conclusion is also different from the opinion[3] that if it were possible to remove all moisture completely, the paper would show no absorption, zero power factor, and 60-cycle capacitance equal to the geometric value. The American investigators deduce, by extrapolation from a pressure of 0·25 mm. Hg, that this condition would be reached at a pressure of 10^{-4} mm. Hg. The present results show experimental values as near this as 4×10^{-4} mm. Hg, with no approach toward "perfect" dielectric properties. The reasons for believing that the paper in this condition was really dry have been given in Section (4)(*a*).

There is every reason to expect that the cellulose molecule, which is a polar one containing three OH groups, will display inherent properties of absorption, with dielectric losses and frequency-dependence of capacitance, after the Debye model. The curves of Fig. 5, though taken over too small a temperature range, are typically those of a polar dielectric (e.g. the rapid increase of the high-frequency loss angle with diminishing temperature), and similar curves for pure dry cellulose are available over a wider range of frequency and temperature.[6] If, therefore, values of capacitance-change or of loss angle are to be used as a criterion of dryness, due allowance must be made for the residual values due to the cellulose itself, at the temperature, and for the type of paper, involved.

Table 3

Sample No.	Temperature	C	δC_0	$\delta C_0/C$	tan δ (50 c./s.) (dry)	tan δ (50 kc./s.) (dry)
	°C.	μμF	μμF			
358	100	500	2·5	0·0050	0·00283	0·00128
358	60	490	2·3	0·0047	0·00080	0·00274
822	60	390	2·17	0·0056	0·00097	0·00306
350	60	539	2·13	0·0040	0·00083	0·00217

The observed increase of capacitance with temperature (see Fig. 5) is also to be expected from a polar solid, over an appropriate temperature range. The American investigators (Reference 3, page 41), ignoring the polar nature of the material, anticipate either constancy of dielectric constant with temperature, or a decrease due to diminishing density, and by applying a large correction for expansion of the electrodes (0·00075 per deg. C.) obtain an approximately constant value. In the present investigation, on the least favourable assumption as to the nature of the electrode movement, the coefficient would be 0·00004, or 19 times smaller than the American value. This figure has been used in obtaining the results of Fig. 5. On the more probable assumption that friction between electrode and paper forces the latter to share in the expansion of the former, the correction would be zero, and the true increase of capacitance would be slightly larger than in Fig. 5. In either case, the increase with temperature is real, but would be masked by a correction such as that employed in the American work which is larger than the effect sought.

(c) The Electrical Characteristics of Water Adsorbed on Cellulose

Since direct determinations were obtained of the quantity of water adsorbed by the samples, it is possible to determine the effective dielectric constant of the adsorbed water, thus reversing the procedure adopted in Reference (3), where the quantity of water was calculated on the basis of an assumed dielectric constant. In this connection the investigation described in Reference (9) is of interest, in which also the quantity of water was directly determined.

There is some uncertainty as to the best method of deducing the effective dielectric constant of water from observations upon a heterogeneous mixture of air, water, and cellulose. J. B. Whitehead[3] and Argue and Maass[9] assume discrete films of water parallel to the field. L. Hartshorn,[8] for a rather different case of water absorbed by synthetic resin, assumes a random dispersion of spherical globules.

Both methods assume the existence of the water in discrete liquid form; an improbable condition for very small quantities of water in the presence of so hygroscopic a substance as cellulose. It is probable, at least for small water content, that the water is present in the form of relatively sparsely distributed molecules on the cellulose surfaces.

This assumption suggests two further, and possibly more accurate, methods of deducing the effective dielectric constant. In one, the water molecules may be regarded as embedded in a medium having the effective dielectric constant of the dry cellulose-air mixture. In the other, the water molecules may be regarded as a polar gas uniformly filling the space between the electrodes, the interaction between the polarizations of the water and the cellulose molecules being neglected.

If κ_1 be the dielectric constant of the dry paper, κ_2 be the dielectric constant of the wet paper, and κ be the dielectric constant of the water vapour; then, provided that κ_1 differs little from κ_2, the first method leads to the result

$$\frac{\kappa - 1}{\kappa + 2} = 3\frac{\kappa_2 - \kappa_1}{(\kappa_1 + 2)^2}$$

On the second assumption, this becomes simply

$$\kappa - 1 = \kappa_2 - \kappa_1$$

It must be realized that κ in these expressions is the dielectric constant of the water, regarded as a gas, at the density at which it exists between the electrodes. Comparisons of such results with those of investigators who have assumed the existence of the water in the liquid phase is difficult, as there is no wholly satisfactory method of reducing the results to a common density.

The Clausius–Mossotti relation

$$\frac{\kappa - 1}{\kappa + 2} \propto \text{Density}$$

is unsatisfactory for a number of reasons. In the first place, the form of the relation makes the value of κ

critically dependent upon the right-hand member when κ is large, as it will be in the case of water. A change in the right-hand member from 0·963 to 1·0 will raise the apparent value of κ from 80 to infinity, and meaningless negative results are easily obtained. It is, further, quite uncertain whether this relation, which is true for gases, will hold at the density of liquid water, or for the condition of molecules adsorbed upon surfaces.

There is at present no satisfactory issue from this difficulty. As a rough method of comparison, it would appear best to assume arbitrarily that $(\kappa - 1)$ is proportional to the density of the water vapour, and in this way reduce all values to unit density for comparison.

Referring now to the experimental results, the dielectric constant of the water might be obtained from the data in two ways: (i) From the values of $\delta C - \delta C_o$. (ii) From the values of ΔC at 50 c./s. The first method implies the assumption that the water does not contribute to the capacitance at 50 kc./s., which is certainly incorrect, as shown by the fall in this capacitance with drying. The second method is theoretically correct, but the values of ΔC, as already explained, are difficult to determine experimentally. For the only two runs for which reasonably reliable values of ΔC are available, the apparent dielectric constant of the water, treated as a gas, at 60° C., is given in Table 4 as calculated from the formulae

Table 4

Sample No.	Run No.	ΔC	W	$\kappa - 1$	ρ	$(\kappa - 1)/\rho$
		$\mu\mu$F	mg.			
358	5	3·65	6·25	0·0134	0·0094	1·43
822	7	13·33	22·8	0·0703	0·0238	2·95

$$\kappa - 1 = \kappa_2 - \kappa_1 = 0{\cdot}25t\Delta C$$

and

$$\frac{\kappa - 1}{\rho} = 1{\cdot}13 \times 10^4 \Delta C \frac{t^2}{W}$$

where t = thickness of sample (cm.); W = weight of water under the active electrode (mg.); and ρ = density of the water, regarded as a gas.

Data for the dielectric constant of free water vapour are scanty, the International Critical Tables (I.C.T.) giving only two formulae over a rather restricted range of conditions. They do not agree well with one another if extrapolated to cover the same range of density, but this may be due to the fact that one was obtained as long ago as 1901. Taking the more recent (1926), we have

$$\kappa - 1 = [9{\cdot}3 - 0{\cdot}026(\tau - 40)]p \times 10^{-6}$$

where $0 < p < 40$ mm. Hg

and $40 < \tau < 165°$ C.

For liquid water, the I.C.T. give

$$\kappa - 1 = 79 - 0{\cdot}4(\tau - 20), \text{ for } 0 < \tau < 100° \text{ C.}$$

These formulae give, at 60° C.,

For the liquid phase, $\kappa - 1 = 63$

For the gaseous phase, $\kappa - 1 = 0{\cdot}00035$ at $\rho = 3{\cdot}45 \times 10^{-5}$

$$\frac{\kappa - 1}{\rho} = 10{\cdot}1$$

The observed values of $\kappa - 1$ for water adsorbed in paper are considerably lower than that for the free vapour, and very much lower than for water in the liquid phase. Since compression of the sample during the run tends to make ΔC too small, some part of the difference may be due to this cause. In addition, the conditions at the beginning of the run are changing rapidly, and the distribution of the water is probably not uniform from the centre to the edge of the sample. The results must therefore be taken as indicating only the order of the dielectric constant. It is hoped to improve the accuracy of these measurements in future work.

Table 5

Sample No.	ρ	$\kappa - 1$ (obs.)	$\kappa - 1$ (free vapour)
358	0·0094	0·0134	0·095
822	0·0238	0·0703	0·240

The low values obtained cannot be attributed to failure to use the Clausius–Mossotti equation, since even if we compare the values not at unit density, but at the actual density of experiment, we obtain a similar discrepancy between the observed dielectric constant and that for free gaseous water, as shown in Table 5. In this range of density the difference between the Clausius–Mossotti relation and simple proportionality to density, is certainly negligible.

Since it may be argued that the low values obtained are due to a faulty assumption regarding the state of dispersion of the water, the effective dielectric constant has been calculated for one case (run No. 7) in all the four ways which have been suggested. The results are shown in Table 6 (κ here referring to values at unit density).

Table 6

Method	κ (calculated)
(1) Discrete films parallel to the field (References 3 and 9)	3·95
(2) Random dispersion of globules (Reference 8)	4·26
(3) Water in gaseous phase, but interaction with cellulose neglected . .	3·95
(4) Water in gaseous phase, correcting for interaction with the polarization of the cellulose	2·62

The exact agreement between Methods (1) and (3) is due to the fact that, although the physical assumptions underlying the two methods are quite different, the resultant expressions for the dielectric constant are identical. The agreement must not, therefore, be used as an argument for the validity of either method.

Whichever method of calculation be preferred, there is no doubt that the polarizability of water adsorbed on cellulose is, for small quantities of water, about one-third of its value for the free vapour, and about one-twentieth that of liquid water. A similar result, though less marked, is shown by the data of Reference (9). The reason doubtless lies in the binding of the water to the cellulose molecules, whereby the freedom of the former to orient in the field is decreased.

If, as a matter of interest without much theoretical meaning, we calculate $(\kappa - 1)/\rho$ from the values of $(\delta C - \delta C_0)$, we can obtain results from four runs, as shown in Table 7. The values are lower than those deduced from the values of ΔC, as would be expected.

Table 7

Sample No.	Run No.	$(\kappa - 1)/\rho$
358	1	0·63
358	5	0·74
822	7	0·96
350	9	0·68

Some further information on the state of the adsorbed water may be obtained by calculating the loss factor ($\kappa \tan \delta$) per unit density of water present. In particular, the variation of this factor with temperature should throw light on the polar nature of the adsorbed molecules and on their state of ionization, since losses due to polarity (if we consider only temperatures above the temperature of the Debye loss-maximum for the molecules concerned) will decrease with temperature and increase with frequency, while losses due to ionic dissociation will have precisely the reverse characteristics. As will be seen, the rather scanty data available from the results support this view.

We define a loss factor

$$\theta = \frac{\kappa \Delta \tan \delta}{\rho}$$

where κ = dielectric constant of sample;
$\Delta \tan \delta$ = change of loss angle as a result of the extraction of W mg. of water;
and ρ = vapour density corresponding to W mg. of water, uniformly distributed between the electrodes.

Table 8 gives values of θ for all runs in which the necessary data were available. In the case of run No. 9, where the water was measured at intervals during the run, it is possible to calculate θ separately for the first 8 mg. of water, and for the final 3 mg., in addition to the average for the whole run.

Table 8

Sample No.	Run No.	Temperature	W	θ (50 c./s.)	θ (50 kc./s.)
		°C.	mg.		
358	1	100	10·6	0·405	0·094
358	5	60	6·25	0·11	0·12
822	7	60	22·8	0·39	0·15
350	9	60	9·4	0·245	0·125 (average for run)
350	9	60	6·8	0·285	0·13 (first part of run)
350	9	60	2·6	0·125	0·11 (second part of run)

Comparing the first two lines of the Table, there appears to be evidence of both polar and ionic losses, as follows:—

(i) At 50 c./s., where the influence of ionic loss is greatest, θ increases with temperature (ionic characteristic).

(ii) At 50 kc./s., where ionic losses should be small, θ falls with increasing temperature (polar characteristic).

(iii) At 100° C., θ falls with increasing frequency (ionic characteristic).

(iv) At 60° C., θ increases with frequency (polar characteristic).

Note also, at 50 cycles per sec., the marked tendency for a large water content to be associated with a high value of θ, possibly due to increased ionization by mutual proximity of the water molecules. At 50 kc./s., where ionic losses are small in any case, the tendency is much less marked.

Work on the nature of these losses will be continued.

(5) CONCLUSIONS

The following are the main conclusions reached:—

(*a*) For temperatures at least as low as 60° C., paper can be brought to a state of complete dryness by the circulation of dry air at atmospheric pressure. Reduction of pressure, while it greatly accelerates the process, does not affect the final result. The conception of residual moisture does not, therefore, apply if the ambient atmosphere be perfectly dry. The equilibria, dependent upon pressure, found by American investigators are probably due to the existence of a partial pressure of water vapour in the atmosphere of their experiments.

(*b*) Paper in the perfectly dry state (as judged from the absence of appreciable change in characteristics when the ambient pressure is reduced 1 million times) shows the electrical characteristics of a polar substance, possessing dielectric losses and a capacitance dependent upon temperature and frequency.

(*c*) Provided that correct allowance be made for the residual values pertaining to the paper itself, either the loss angle or the frequency change of capacitance may be used as an indication of the amount of water present.

(*d*) The polarizability of water adsorbed on cellulose is roughly 3 times less than the polarizability of water in the gaseous state, and 20 times less than that of liquid water.

(*e*) The dielectric loss of water adsorbed on cellulose depends upon temperature and frequency in such a way as to suggest that both polar and ionic loss mechanisms are present.

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APPENDIX

Drying Time as a Function of Shape of Electrode System

To investigate the influence of the shape of sample on the time required to dry it, we assume that a time-constant (T) can be calculated such that

$$T \propto \int \delta \text{ Volume} \times \frac{\text{Length of exit path from } \delta V}{\text{Area of exit path from } \delta V}$$

Then, for a hollow cylinder of half-length L, radii r_1, r_2, assuming that the water can escape only at the ends, we have

$$T \propto \int_0^L \pi(r_1^2 - r_2^2)\left[\frac{l}{\pi(r_1^2 - r_2^2)}\right]dl = \int_0^L l\,dl = \frac{L^2}{2}$$

For a disc of radius R, thickness t, and exit at the periphery only, we have

$$T \propto \int_0^R 2\pi rt \int_r^R \frac{dr}{2\pi rt}dr = \int_0^R r \int_r^R \frac{dr}{r}dr = \frac{R^2}{4}$$

Comparing the American samples (but neglecting the small holes with which they were pierced) with our own, we have

$$L = 30 \text{ cm.}, T_L = 450$$

$$R = 3\cdot 8 \text{ cm.}, T_R = 3\cdot 6$$

$$\frac{T_L}{T_R} = 125$$

For an annular disc, from which water may escape at both inner and outer peripheries, there will be some median radius r_m across which there is no flux of water. We assume that this radius divides the sample into two annuli having each the same value of T. Let R and r_0 be the outer and inner radii respectively. Then

$$T \propto \int_{r_m}^R r \int_r^R \frac{dr}{r}dr$$

and

$$T \propto \int_{r_m}^{r_0} r \int_r^{r_0} \frac{dr}{r}dr$$

From this,

$$r_m^2 = \frac{1}{2}\,\frac{R^2 - r_0^2}{\log_e \dfrac{R}{r_0}}$$

and

$$T = \frac{1}{4}(R^2 - r_m^2) - \frac{r_m^2}{2}\log_e \frac{R}{r_m}$$

Taking an annulus with $R = 4\cdot 5$ cm., $r_0 = 2\cdot 41$ cm., which will have the same area as the 3·8-cm. solid disc, we obtain $r_m = 3\cdot 4$ cm., $T = 0\cdot 58$. The particular annulus chosen, therefore, gives an improvement of 6 to 1 in drying time, with an increase in external diameter of only 18 %. There is no information to indicate how far these mathematical results would be borne out in practice.

DISCUSSION ON

"THE METADYNE, AND ITS APPLICATION TO ELECTRIC TRACTION"*

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL,
20TH NOVEMBER, 1939

Prof. F. J. Teago: Although the metadyne is a new piece of apparatus in one sense, it is not altogether new because Dr. E. Rosenberg in 1905 published the details of his constant-current dynamo and Prof. J. C. Prescott† showed in 1925 that a non-salient-pole construction was a feasible proposition for this class of machine. Prof. J.M. Pestarini's valuable contribution to the development of the idea appears to be the "eight" connection, and in the interests of those attempting to understand the theory it should be emphasized that the "eight" connection is most accurately described as a metadyne rheostat.

Rapid short-distance transport calls for high values of acceleration and deceleration and, in consequence, may be costly; so that any innovation affecting acceleration and deceleration is worthy of close examination. The metadyne is a promising accelerator because it readily supplies a smooth current, and it is a useful decelerator because it provides such an easy way of connecting series generators to a live line.

The authors have not, however, made out a clear case for the metadyne on that most important score "cost," since the paper is mainly devoted to theory and application. Taking everything into consideration one cannot say that the metadyne is simple and cheap. Food for thought on this question is provided when one calls to mind the modern trolleybus equipment for handling the problems of acceleration and deceleration connected with rapid short-distance transport on the public highway. It may be contended that there is little in common between a trolleybus system and a suburban electric railway, but it must not be forgotten that tap and shunt-field control have been applied to railway motors and that compound field windings are used even on the metadyne.

Owing to the fact that by no means all the axles of an electric train are usually motored and that truck equalization is not fully utilized one cannot say that the limits of common practice have been attained, particularly where fine controller notching is possible and compound field windings are permissible.

Mr. R. Varley: From information given by the authors it seems quite probable that the metadyne will be extensively adopted for electric traction in cases where the additional cost can be justified. There also appears to be scope for its adoption in other directions, such as for gearless lifts or similar equipment where smooth acceleration and deceleration are required.

I notice that the authors give the reduction in the amount of brake dust as one of the advantages of the equipment. So far as electrically-driven stock is concerned, this advantage is to a large extent being eliminated by the use of non-metallic brake blocks.

One point on which I should like further information is with regard to the mounting of the metadyne. It appears to me that there may be some difficulty in mounting the metadyne in a position where it is readily accessible for inspection and maintenance.

From the figures quoted, the equipment appears to be efficient; but information would be welcome as to how the energy consumption of a train equipped with the metadyne compares with that of a train of similar weight and speed equipped with the ordinary rheostatic control.

Major G. W. Parkin: The application of the metadyne to electric traction has enabled the heavy-service operator to obtain those operating characteristics for which he has long been seeking, namely practically constant-current acceleration without rheostatic losses coupled with regenerative braking almost down to a standstill.

I do not consider that we need be unduly concerned about the maintenance costs of this additional piece of rotating equipment to be carried on each tractive coach, but its weight of almost 4 tons is a factor warranting careful thought. Under conditions where the regenerative feature cannot be employed one would anticipate that the power saving due to elimination of rheostatic acceleration losses would be largely offset by the greater amount of energy expended during braking and the increased wear and tear generally, due to increased train weights. When regenerative braking is feasible, however, the advantages of the metadyne are very real, as is witnessed by the authors' statement that tests have shown that two-thirds of the total energy of braking can be returned to the line, and this under conditions sufficiently severe to call for mechanical braking on all non-motored axles during the period for which regenerative braking is applied to the motored axles.

When it is appreciated that each coach running to a typical underground schedule is responsible for the production of probably 1 ton of brake dust annually, with its attendant detrimental effects on the maintenance, any scheme providing for a reduction in mechanical braking should obviously be encouraged.

In conclusion, I should like the authors to state what delays are experienced owing to waiting for the metadyne to run up to balancing speed after temporary loss of line voltage; and whether the machine is free from commutation troubles under the conditions of rapidly fluctuating line voltage which are typical of a traction load.

Mr. O. I. Butler: In the first sentence of the paper the authors define the term "Metadyne" as including various forms of dynamo having additional brush-arms intermediate between the usual brush-arms. The authors themselves consider only that case in which the additional brush-arms are midway between the usual brush-arms.

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* Paper by Messrs. G. H. Fletcher and A. Tustin (85, p. 370).

† *Journal I.E.E.*, 1925, 63, p. 206.

Referring to Fig. A, it will be evident that with the additional brush-arms in any other position such as B_1D_1 or B_2D_2, etc., different performance characteristics will be obtained for the metadyne. Finally, when the additional brush-arms are moved to coincide with the usual brush-arms, the metadyne will take the form of the ordinary dynamo or motor. This leads to the interesting conclusion that, instead of the metadyne being a special form of d.c. machine, the ordinary d.c. motor or generator is actually a special form of the metadyne. Thus, accepting the authors' definition, the term "metadyne" may be said to cover all types of d.c. machines, of which the ordinary d.c. motor and generator are only two. Other types exist according to the position of the additional brushgear. Also, besides including the motor and the generator, the term "metadyne" is used to cover the case of the d.c. transformer, which is the machine chiefly dealt with in the paper.

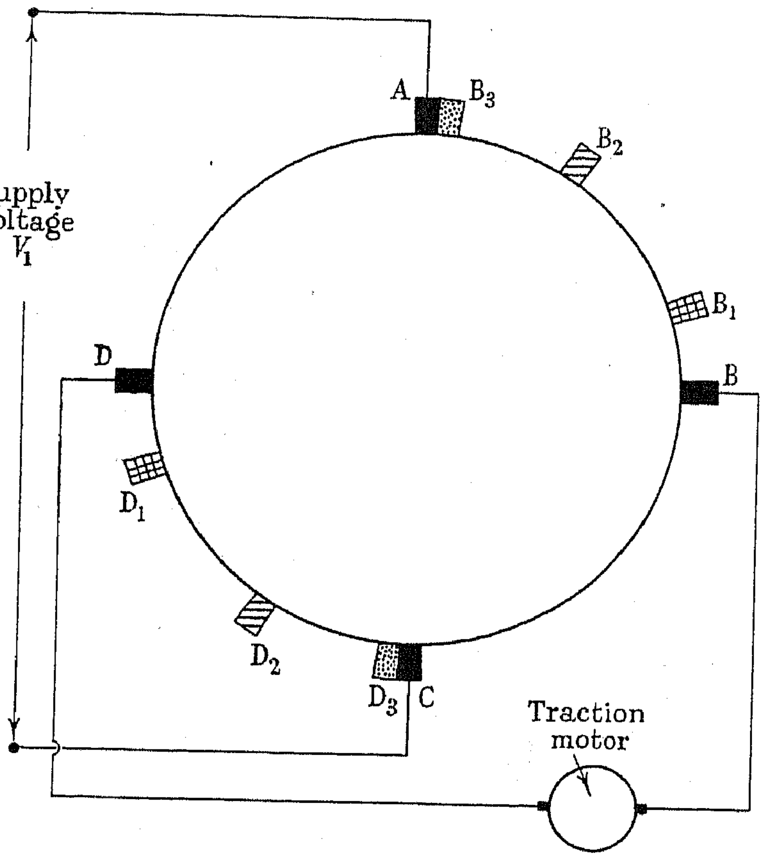

Fig. A

An alternative, and possibly simpler, method of showing that a metadyne without a stator winding is a d.c. transformer, is given by a physical consideration of the machine. It is well known that a force can only exist when there is action and reaction. If no excitation windings exist on the stator, then there is no stator flux to allow of action and reaction between the armature conductors and the stator. That is, the armature conductors have nothing to "push" against, and so no external force can exist at the surface of the armature. It follows that no external torque exists, and so no mechanical work is done in rotating the metadyne armature at a constant speed, if we neglect incidental losses such as that due to friction. Thus the input and output are wholly electrical, and the machine is an electrical transformer.

Turning to the question of motoring and regenerating peaks, the record of the line current given in Fig. 20 shows a motoring entry peak of about 400 amperes and a regenerating entry peak of about 100 amperes. Although the latter peak is the smaller, it appears probable that it would have the more serious effect on the riding comfort of the passengers since, although it is intended to commence retardation of the train at a given instant, the positive direction of the peak indicates that the reverse function takes place. That is, an accelerating peak occurs, followed by the desired retardation as the line current reverses its direction of flow.

It may be of interest to refer to Fig. B,[*] which shows two oscillograph records taken on an experimental metadyne which has been in operation for several years at the University of Liverpool under the supervision of Prof. F. J. Teago. In order to eliminate motoring and regenerating entry peaks, the inductance in both the primary and the secondary power circuits of the metadyne was kept down to a minimum. For this reason, series-field turns on the traction motors were avoided, the main-pole windings being separately excited by a low-voltage heavy-current supply and the high starting-torque characteristic of the motors being retained.

Also, the cross-connection scheme of the metadynes used on the Paris–Orléans Railway shunting locomotives was adopted in preference to the "eight" connection of the metadynes operating on the railways of the London Passenger Transport Board, in order to eliminate the (apparently) practical necessity for disturbing and breaking the secondary circuit during the transition from the motoring to the regenerating condition. It was felt that the metadyne should permit of a direct and smooth transition from motoring to regenerating without the necessity of interposing a period of coasting or any temporary break in the power circuits, no matter how quickly the break might be rectified.

The oscillograph records of Fig. B show the almost perfect smoothness of the transition from the motoring to the regenerating condition, and would appear to substantiate the foregoing remarks on the possibility of avoiding current peaks. Fig. B(i) is a record of the current in the primary circuit, whilst Fig. B(ii) is a record of the current in the load or secondary circuit. A 50-cycle supply was used as a time-base, whilst the camera was rotated by hand.

Fig. B(i) shows that the time taken for the primary current to fall to zero, from a motoring value of approximately 20 amperes at the instant of change-over, is about $1\frac{1}{2}$ sec. The interval of regeneration is then approximately 5 sec., followed by an interval for motoring of about 1 sec., at the end of which the traction motor has been brought to a complete standstill and the primary supply then cut off. Fig. B(ii) shows the secondary current during a regenerative interval of approximately 3 sec., followed by the interval of about 1 sec. in which electric braking of the traction motor occurs down to standstill.

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[*] Taken from *Railway Gazette* (*Electric Railway Traction Supplement*), 1938, **69**, p. 475.

The traction motor was loaded by being mechanically coupled to a heavy flywheel, and regeneration was effected by the simple expedient of reversing the separately-excited field of the traction motor, without the intermediate entry step required by the " eight "-connected metadyne, as described by the authors.

A valuable characteristic of the metadyne, which the authors do not appear to mention, is that the load current I_2 increases inversely as the speed of the metadyne for a given line voltage. It would appear that this characteristic is of considerable value in traction work, where the line voltage is liable to excessive variation; as, although a fall in line voltage results in a corresponding fall of the excitation current I_2, the consequent fall in speed of the regulator motor and metadyne will tend to maintain I_2 at a constant value. Is any attention paid to the saturation curves of the metadyne and the regulator to ensure that the load current I_2 is independent of possible changes in the line voltage?

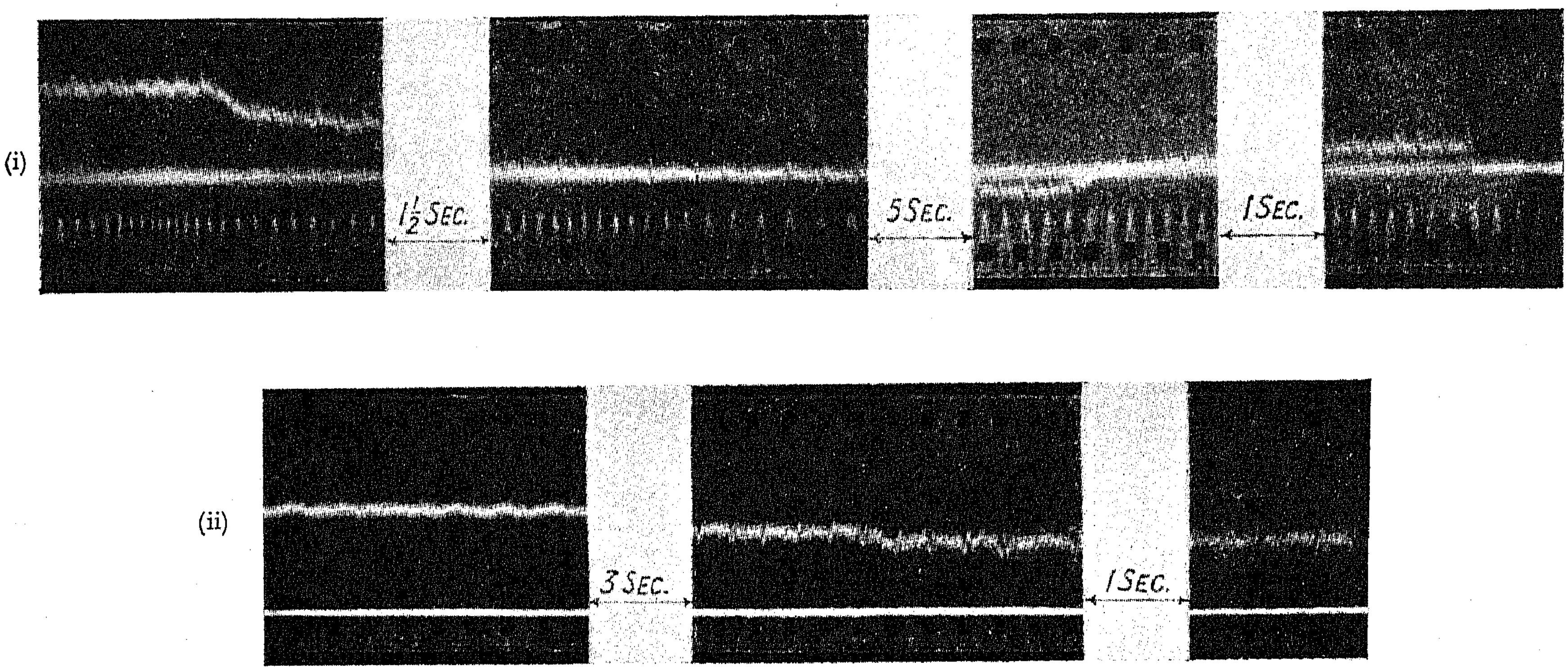

Fig. B

Little mention is made of commutation in the paper, presumably because as the result of experience with other armature-reaction machines, such as the Rosenberg dynamo, commutation is no longer the limiting factor in the design. The stator arrangement shown in Fig. 1 indicates that the commutation of the metadyne currents is essentially similar to that of an ordinary 4-pole dynamo or motor, fitted with interpoles. A slight complication appears possible due to the fact that, during the major time of operation, the current in the metadyne conductors is not reversed from a given positive value to an equal negative value, or vice versa, as in ordinary d.c machines.

One cannot fail to admire the ingenuity displayed in the design of a practical metadyne. There is little doubt that its characteristics are such as to make its application of considerable value in many fields other than electric traction.

Mr. J. E. Macfarlane: We have to bear in mind that with the addition of the metadyne a number of extra commutators are embodied in the plant. The brushes on the metadyne are not in the best commutating position, so it would appear that further means beyond those shown in the authors' simple diagrams are necessary to ensure satisfactory commutation. Ought we not to debit against the savings on brake wear the further maintenance costs involved for the additional commutators required when the metadyne is installed?

Mr. D. G. O. Morris: I should be glad if the authors would state by what currents the interpoles are excited, and how the interpole fluxes respond to the very severe transient conditions to which the metadyne has to stand up in tests, e.g. the open-circuiting of the line and the short-circuiting of the motors.

Lieut.-Col. H. E. O'Brien: Second only in interest to the saving effected in energy consumption on the train by the use of the metadyne are the other advantages referred to on page 381, namely the economy in brake-block consumption and in tyre wear, and the reduction in the production of metallic dust. A further advantage is the possibility of equalizing substation loads and steadying the line voltage by the use of storage batteries capable of high rates of charge and discharge: it is clearly impossible to say whether this last arrangement would be economical without working out an example.

The authors seem to make no mention of the weight of these metadyne equipments as compared with that of normal contactor equipment: the weight presumably has a fairly close relation to the speed of the metadyne unit, which is not mentioned in the paper. In this connection I have heard something of a non-ferrous alloy with a much higher magnetic permeability than iron: it seems to be desirable if possible to use a material having the very highest permeability, in order to reduce weight.

The description of the shunting locomotive for the

Paris–Orléans railway is particularly interesting as it introduces the old problem of how to deal with shunting at wayside stations, and indeed also in large goods yards. Would the elimination of the overhead equipment for sidings be possible if all freight locomotives were built on the lines of this shunting locomotive? Would the cost of the accumulators, etc., and their maintenance be greater than that of the overhead equipment and its maintenance?

It must be remembered what an enormous siding mileage is in being on those main lines with sufficiently dense traffic to warrant electrification. This is a fascinating accountancy-cum-engineering problem, into which the operating side enters to some extent, because if locomotives are not earmarked for freight passenger service, passenger locomotives may require to use the sidings.

The third-rail system is still with us, and were it not for the clearance difficulties on British railways it would still be a proposition worth considering for 1 500 volts in these days of rectifier substations with automatic control, particularly if the outdoor rectifier substation had materialized. The clearance difficulty can be overcome, but I mention the third rail for another reason, namely the effect produced on the metadyne by gaps in the third rail. Have any difficulties arisen?

Messrs. G. H. Fletcher and A. Tustin (*in reply*): We agree with Prof. Teago that it is to be expected that electric motor-coach trains will develop along the lines of the motoring of a larger number of axles. This is not an alternative to the metadyne, but will enable the special properties of the metadyne to be more fully utilized, since, for example, the braking may then be completely regenerative and accelerations and retardations may be increased still further without discomfort to passengers.

Prof. Teago also suggests that the metadyne in the "eight" connection is most accurately described as a metadyne rheostat. We suggest that it would be better to regard it as a d.c. auto-transformer, since the idea of a rheostat is associated with losses of power.

We would refer Mr. Varley to the contribution to the discussion made by Mr. Graff-Baker,* who has promised that tests will be carried out to ascertain the actual overall economy achieved in service by the use of metadynes as compared with standard equipments. The difficulties of assessing overall service economy except by test are explained in an earlier reply.

With regard to the use of non-magnetic brake blocks, while this may be possible where low adhesion forces are required, considerable difficulties have been experienced where the adhesive forces are rather high owing to polishing of the wheel tyres, and consequent reduction of adhesion. Furthermore, we understand that the use of non-metallic brake shoes does not give a reduction in the cost of replacements.

Major Parkin asks what delays are experienced owing to waiting for the metadyne to run up to speed after temporary loss of line voltage. The total time to accelerate the metadyne from rest to its normal speed is less than ½ minute, but the temporary interruption of the supply voltage does not cause the metadyne to come to rest, and in general any such interruptions are so short that practically no speed is lost, and there is no noticeable delay in the recommencement of operation when the voltage is remade.

We are interested in the contribution of Mr. Butler, and in his description of the experimental results obtained on a small metadyne. Mr. Butler calls attention to the initial kick of current in the motoring direction which is shown at the commencement of regenerative braking in Fig. 20. In later equipments this momentary reversal of current does not occur, because the method of exciting the metadyne prior to connection to the line has been improved, as explained in the paper. The commencement of regeneration is actually perfectly smooth and results in no discomfort to the passengers.

No attempt is made in the design of the metadyne to compensate for the effect of the line voltage on the output current, by a corresponding change in speed of the set. This is because the design of the regulator motor is chiefly controlled by the necessity of obtaining as large a change of current in the metadyne regulator winding as possible when the load conditions on the metadyne vary. For this reason the metadyne regulator is designed as a shunt machine without saturation.

Mr. Macfarlane raises the question as to whether special commutating arrangements are necessary on metadynes. This point has been fully dealt with in a previous reply. The flux in the interpole responds to sudden changes of the current in exactly the same way as it does in an ordinary dynamo. Mr. Morris asks whether these flux changes respond to very severe transient conditions. The difficulties of design in these cases are exactly the same as in an ordinary dynamo, and may be met by lamination of the interpoles and by proper design of the interpole magnetic circuit.

In reply to Lieut.-Col. O'Brien, the speed of the metadyne in use on the London Passenger Transport Board's system is 1 630 r.p.m.

The presence of gaps in the third rail which cause interruptions of the supply has no noticeable effect on the operation of the metadyne when motoring; but if such gaps are encountered during regeneration they cause the relay to operate, thereby bringing in the braking resistor across the metadyne so that braking continues, the power being absorbed by the resistor. This arrangement has operated quite satisfactorily.

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MODIFICATIONS OF THE LEBLANC PHASE-ADVANCER*

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SUMMARY

This paper deals with modifications of the Leblanc phase-advancer in which the compensating effect of the phase advancer can be varied, within wide limits, without changing the speed of the phase advancer.

The first modification is that of providing two sets of brushes on the commutator of the standard Leblanc phase-advancer, as in the Schrage motor. The compensating effect of the phase advancer can be varied by altering the angle between the brushes. This modification has certain objectionable features and is not considered desirable.

In the second (and best) modification the phase advancer is provided with a stator and a stator winding, and the latter is closed through a rheostat. The compensating effect of the phase advancer is increased or decreased by decreasing or increasing the resistance in the circuit of the stator winding of the phase advancer.

The third modification is to provide a commutator winding and a slip-ring winding on the rotor, and to close the latter through a rheostat. The compensating effect of the phase advancer is increased or decreased by increasing or decreasing the resistance in the circuit of the slip-ring winding of the phase advancer.

The fourth modification, a combination of the two preceding ones, is rather complicated and does not offer any special advantages. It is easily made available, however, being essentially the same as the Schrage motor, and is useful for the study of the second and third modifications.

The results of an experimental study of the second and third modifications, made with the help of a Schrage motor, are given.

The theory of the Leblanc phase-advancer with stator winding and additional rotor winding is worked out with the help of vector diagrams and equivalent circuits. The method of predetermining the current locus and the performance curves of a motor connected to either type of phase advancer is given and is applied to a 150-h.p. motor.

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(1) LIST OF SYMBOLS

All the currents, voltages, resistances, and reactances in the induction motor and the phase advancer, unless otherwise specified, are per phase (star), reduced to the primary of the induction motor. The symbols which will be adopted for them are as follows:—

$$A = \frac{(c-s)x_0'R_2'/s}{s[(R_2'/s)^2 + x_0'^2]}$$

$$= \frac{c-s}{s}\cos\theta\sin\theta$$

$$B = \frac{(c-s)x_0'R_2'}{R_2'^2 + (c-s)^2x_0'^2}$$

$$= \sin\theta\cos\theta$$

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LIST OF SYMBOLS—*continued.*

$-E$ = voltage induced in the primary of the induction motor by its air-gap flux;
$-E'$ = voltage induced in the primary of the phase advancer by its air-gap flux;
E_1 = voltage impressed on the primary of the induction motor;
E_1' = voltage impressed on the primary of the phase advancer;
I_0 = exciting current of the induction motor;
I_0' = exciting current of the phase advancer;
I_1 = current in the primary of the induction motor;
I_1' = current in the primary of the phase advancer;
$-I_2$ = current in the secondary of the induction motor;
$-I_2'$ = current in the secondary of the phase advancer;
N_a = speed of the phase advancer, in r.p.m.
N_s = speed (in r.p.m.) of the rotating flux of the phase advancer when it is supplied with 3-phase alternating currents of frequency f and is stationary;
R = resistance of the main circuit in the equivalent circuit of the induction motor connected to a phase advancer;
R' = external resistance (not reduced to primary of the induction motor) in the circuit of the secondary of the phase advancer;
R_2 = sum of the resistances of the induction-motor secondary and the phase-advancer primary $= r_1' + r_2$;
R_2' = sum of the resistance of the secondary of the phase advancer and the external resistance in the secondary circuit of the phase advancer;
X = reactance of the main circuit in the equivalent circuit of the induction motor connected to a phase advancer;
$Z = \sqrt{(X^2 + Y^2)}$;
$c = N_a/N_s$;
f = frequency of supply to the induction motor;
$j = \sqrt{(-1)}$;
k_a = ratio of transformation of the phase advancer;
k_m = ratio of transformation of the induction motor;
p_a = number of poles of the phase advancer;
r_0 = exciting resistance of the induction motor, i.e. the equivalent resistance corresponding to the iron losses of the motor;
r_1 = resistance of the primary of the induction motor;
r_1' = resistance of the primary of the phase advancer;
r_2 = resistance of the secondary of the induction motor;
s = fractional slip of the induction motor;
(x, y) = co-ordinates of the extremity of the current in the main circuit;
x_0 = exciting reactance of the induction motor at supply frequency;
x_0' = exciting reactance of the primary of the phase advancer at supply frequency;
x_1 = leakage reactance of the primary of the induction motor at supply frequency;
x_1' = leakage reactance of the primary of the phase advancer at supply frequency;
x_2 = leakage reactance of the secondary of the induction motor at supply frequency;

LIST OF SYMBOLS—*continued.*

x_2' = leakage reactance of the secondary of the phase advancer at supply frequency;
θ = phase difference between $-E'$ and I_1';
θ' = phase difference between E' and I_1';
ψ = phase difference between E_1 and I_2;
ϕ_0 = phase difference between E_1 and I_0;
ϕ_1 = phase difference between E_1 and I_1;
Φ' = flux in the air-gap of the phase advancer.

(2) INTRODUCTION

In practice a phase advancer is arranged to run at approximately constant speed, by coupling or belting it to the motor which it is compensating, or by driving it separately by a small squirrel-cage induction motor. The action of a constant-speed series phase advancer of the Miles Walker type can be varied by rocking the brushes, but this is only possible when the phase advancer is over-compensated. For the Scherbius phase advancer, it is the standard practice to connect a rheostat in the stator circuit. By varying the resistance in the stator circuit, the action of the phase advancer can be varied between wide limits. In the case of the Leblanc phase-advancer, rocking the brushes does not produce any effect, and the only way of altering the action of the phase advancer is by changing its speed. This, however, is not a practical proposition. The object of this paper is to describe and discuss certain modifications of the Leblanc phase-advancer in which the compensating effect of the phase advancer can be varied without altering the speed of the phase advancer.

(3) STANDARD LEBLANC PHASE-ADVANCER

Fig. 1 shows a diagrammatic sketch of a standard 2-pole Leblanc phase-advancer, which in its simplest form comprises a d.c. armature P_a with three brushes resting 120° apart on the commutator. The phase advancer is either coupled or belted to the motor to be compensated or is driven separately by a small squirrel-cage induction motor. The brushes of the phase advancer are connected to the secondary S of the induction motor as shown in Fig. 1. The primary P of the motor is connected to the supply.

The brushes of the phase advancer, as also of the modifications described below, are connected to the secondary of the induction motor in such a way that the currents of slip frequency flowing into the phase advancer from the secondary of the motor set up in the phase advancer a rotating flux in the direction of rotation of the phase advancer. The phase advancer is run at a speed greater than that of its revolving flux, and a voltage leading the secondary current by 90° is generated in the phase advancer.

(4) MODIFICATIONS OF THE LEBLANC PHASE-ADVANCER

(a) Leblanc phase-advancer with three pairs of brushes

One modification of the Leblanc phase-advancer is obtained by providing it with three pairs of brushes—a_1a_2, b_1b_2, c_1c_2—as shown in Fig. 2. Brushes a_1, b_1, c_1 are mounted on one brush rocker and are 120° apart. Brushes

a_2, b_2, c_2 are mounted on another rocker and are also 120° apart. The two rockers are connected together by a rack-and-pinion arrangement as in the Schrage motor, so that the angle between the brush pairs can be altered symmetrically by rocking the brushes.

The three pairs of brushes are connected to the three phases of the secondary, which must be in three separate sections. The connections are such that the secondary currents flowing into the phase advancer set up a rotating flux in the direction of rotation of the phase advancer, and a voltage leading the secondary current by 90° is generated in the phase advancer. For a given secondary current and phase-advancer speed, the voltage between a pair of brushes depends on the angle between the brushes, and the action of the phase advancer can be varied between wide limits by rocking the brushes. Another advantage is that the maximum voltage that can be obtained from the commutator is 15 % more than with the standard Leblanc phase-advancer, as the brushes can now be separated by 180° instead of 120°.

The disadvantages are that (i) the secondary, if on the rotor, must have six slip-rings, or the secondary must be on the stator and the primary on the rotor; and (ii) the current in each phase of the phase advancer is no longer $1/\sqrt{3}$ times the line current but is equal to the line current. Thus when the brushes are 120° apart the copper losses in the phase advancer are 3 times those in the standard Leblanc phase-advancer. Owing to these disadvantages, this modification of the Leblanc phase-advancer is not a desirable one.

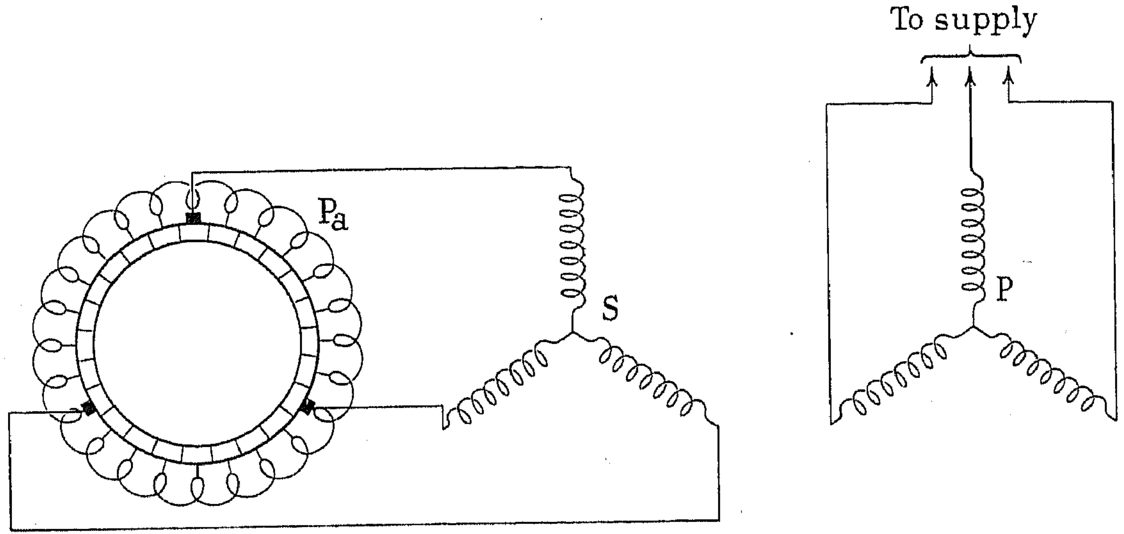

Fig. 1.—Diagram of connections of induction motor and standard Leblanc phase-advancer.

(b) Leblanc Phase-advancer with a Stator and a Stator Winding

All types of phase advancers other than the Leblanc type have a stator and one or more stator windings. Therefore there can be no objection to adding a stator and a stator winding, or an additional rotor winding, to the Leblanc phase-advancer, if this is going to improve its performance to a considerable extent.

Fig. 3 is a diagrammatic sketch of a 2-pole Leblanc phase-advancer with a stator and a stator winding. P_a is a commutator winding on the rotor, and will be referred to as the primary of the phase advancer. The brushes on the commutator are 120° apart and are connected to the slip-rings of the induction motor to be compensated exactly as with the standard Leblanc phase-advancer; that is, in such a way that the currents from the secondary of the induction motor set up a rotating flux in the phase advancer revolving in the direction of rotation of the phase advancer.

S_a is a 3-phase winding on the stator and will be referred to as the secondary or the stator winding of the phase advancer. It is connected to a rheostat through a switch, so that the resistance in the stator circuit can be varied from infinity to various finite values.

(c) Leblanc Phase-advancer with an Additional Winding on the Rotor

Fig. 4 is a diagrammatic sketch of a 2-pole Leblanc phase-advancer with two windings on the rotor. P_a is the commutator winding and is referred to as the primary of the phase advancer. The brushes on the commutator are 120° apart and are connected to the slip-rings of the induction motor in exactly the same way as in the standard Leblanc phase-advancer. S_r is a 3-phase winding which will be referred to as the secondary or the slip-ring winding of the phase advancer. It is located in the same slots as the commutator winding and is brought out to three slip-rings, through which it is connected to a rheostat.

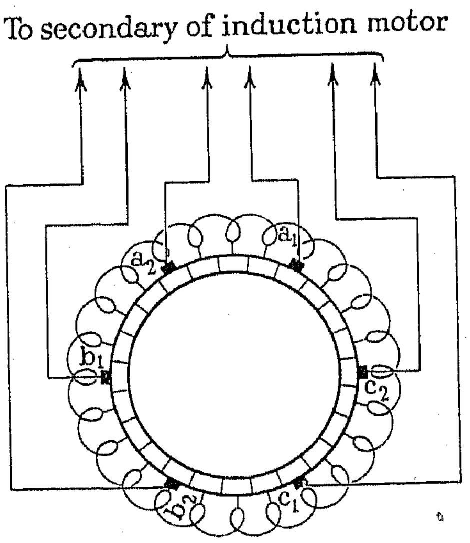

Fig. 2.—Diagrammatic sketch of Leblanc phase-advancer with two sets of brushes.

(d) Leblanc Phase-advancer with a Stator Winding and an Additional Rotor Winding

Another possible modification of the Leblanc phase-advancer is a combination of (*b*) and (*c*) above; it is shown in Fig. 5. The rotor contains a commutator winding P_a and a slip-ring winding S_r connected to a rheostat through a switch. The stator has a 3-phase winding S_a connected to a rheostat through a switch. The stator and slip-ring windings are the two secondaries of the phase advancer, and the commutator winding is its primary.

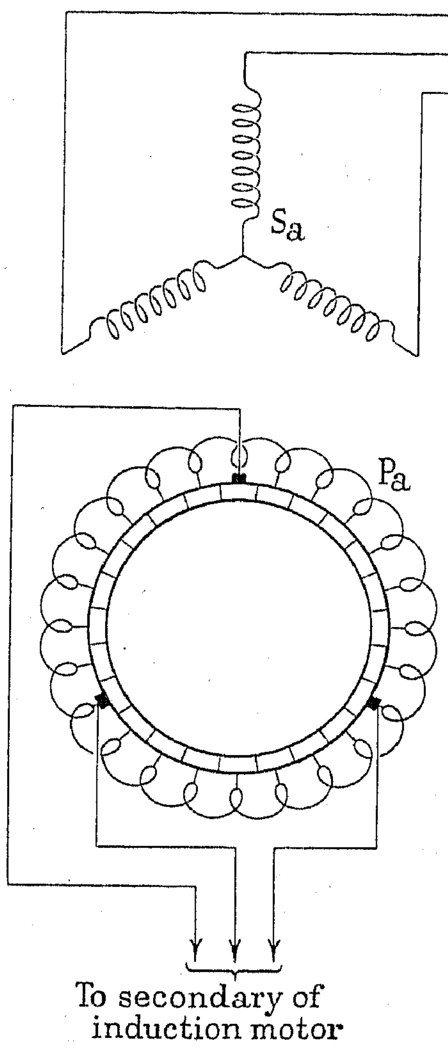

Fig. 3.—Diagrammatic sketch of Leblanc phase-advancer with stator and stator winding.

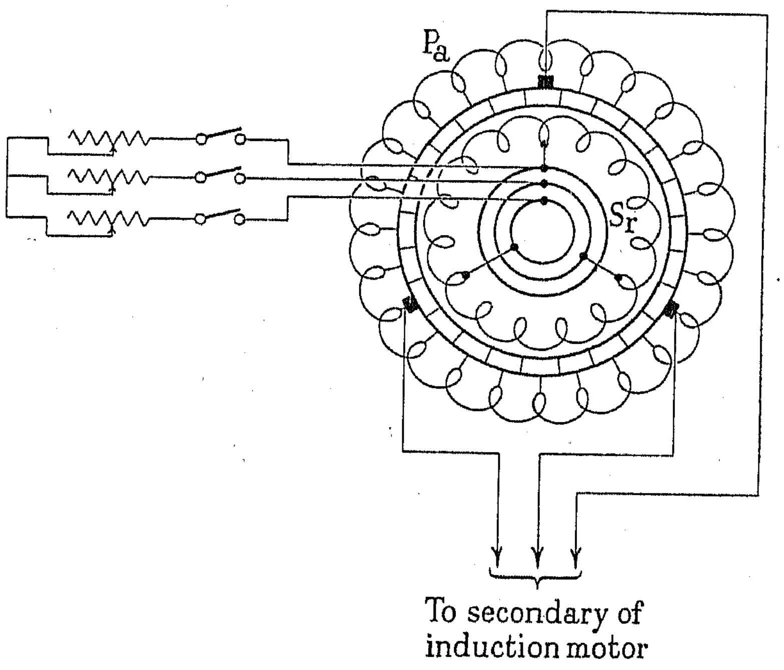

Fig. 4.—Diagrammatic sketch of Leblanc phase-advancer with an additional rotor winding.

This is rather a complicated phase-advancer, and tests show its compensating action to be poor. But it is readily available, being essentially the same as the Schrage motor, and can be used for making a preliminary study of modifications of the Leblanc phase-advancer having a stator winding or an additional rotor winding. The author used a Schrage motor for the experimental study described in this paper.

The commutator brushes are connected to the slip-rings of the induction motor as in the standard Leblanc phase-advancer.

(5) TEST RESULTS OF LEBLANC PHASE-ADVANCER WITH A STATOR WINDING AND AN ADDITIONAL ROTOR WINDING

The Schrage motor which was used for the author's experimental study is a 2- to 6-h.p., 100-volt, 4-pole, 25-cycle machine. The turns per phase of the slip-ring winding and of the commutator winding between brushes 120° apart, are in the ratio 1:0·226. The inductive motor used with the phase advancer is a 7·5-h.p., 100-volt, 4-pole, 50-cycle machine. It is really too small for the phase advancer, but was the largest machine available to the author. The number of turns on the primary is the same as on the secondary.

Load tests were carried out with the slip-ring winding open and with various constant resistances (R') in the stator or secondary circuit of the phase advancer. The phase advancer was driven at a constant speed of 750 r.p.m. The primary-current loci for various cases are shown in Fig. 6. OE_1 represents the voltage impressed on the primary of the motor, and OA ($= I_0$) the magnetizing current of the motor. Curves A, B, and C are the current loci of the motor for values of $R' = 0{\cdot}24$ ohm, 0·96 ohm, and 3·34 ohms respectively, introduced in the phase-advancer stator circuit. Curve D is the current locus with the stator circuit open, or, in other words, with the machine used as a standard Leblanc phase-advancer. These curves show that the provision of a stator winding not only increases the compensating effect of the Leblanc phase-advancer but makes it possible to vary its action within wide limits. The power factor near no-load is always lagging, which indicates that this phase advancer possesses the characteristic of the standard Leblanc phase-advancer.

The compensating effect of the phase advancer increases as the resistance in its stator circuit is decreased. One is inclined to expect that maximum compensation might be obtained with the stator winding short-circuited; but this is not the case. With the stator winding short-circuited, the current locus is the curve E, and the effect of the stator winding is definitely harmful. An important conclusion to which the curve E leads is that the compensating effect of the phase advancer is a maximum for some value of resistance in the stator circuit, and if the resistance is less or greater than this the compensating effect is reduced.

Curve F is the theoretical current locus of the induction motor with its secondary short-circuited, and is shown here for purposes of comparison.

Fig. 7 shows the slip (s) and the primary power factor ($\cos \phi_1$) of the motor with a constant secondary current of 35 amperes and with various external resistances (R') in the stator circuit of the phase advancer. Curve E_r shows the voltage induced in the open-circuited slip-ring winding of the phase advancer. Curve I_s shows the current in the stator circuit of the phase advancer. The phase advancer was driven at a constant speed of 750 r.p.m. From the curve E_r in Fig. 7 it will be seen that for values of R' from 0·24 ohm to 2·88 ohms the voltage in the open-circuited slip-ring winding is very nearly constant and has an average value of about 51 volts. This voltage is proportional to the voltage induced in the commutator winding, and it is therefore concluded that the voltage induced in the commutator winding is practically constant. It will be observed that as the resistance in the stator circuit is reduced from 2·88 ohms to 0·24 ohm, the slip of the motor decreases from 10·6 % to 2·7 %, and the current in the stator circuit of the phase advancer increases from 2 amperes to 10 amperes.

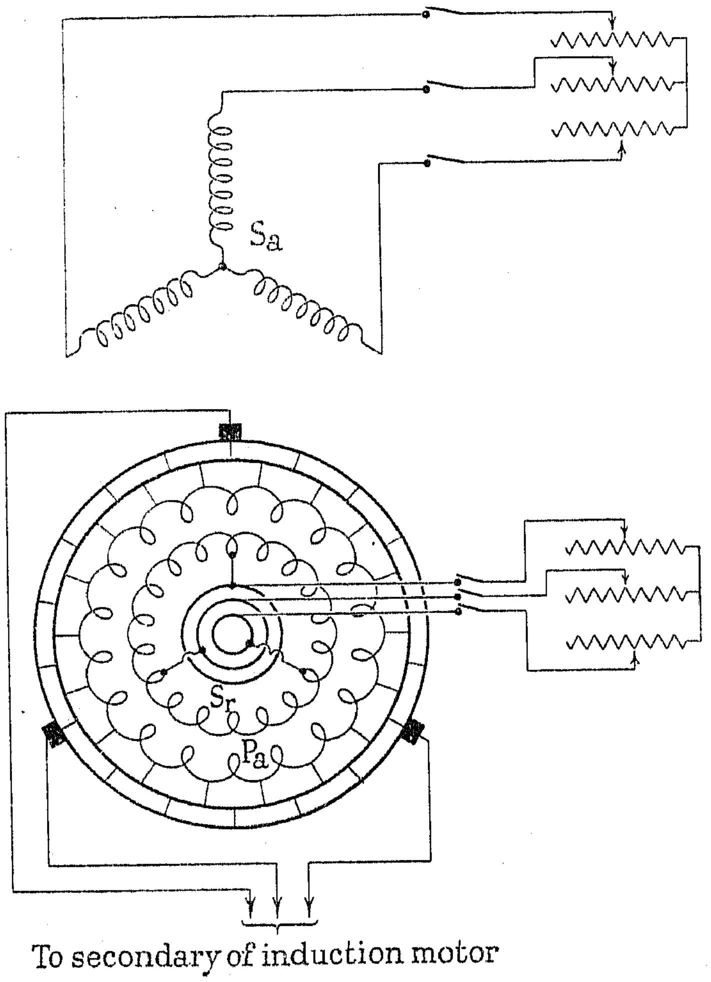

Fig. 5.—Diagrammatic sketch of Leblanc phase-advancer with stator winding and an additional rotor winding.

It was remarked in connection with the current loci of Fig. 6 that, for some value of resistance in the stator circuit of the phase advancer, the compensating effect of the phase advancer is a maximum. An examination of the power-factor curve in Fig. 7 shows that this resistance is about 0·25 ohm. The compensating effect decreases sharply as the resistance is reduced, but much less sharply when the resistance is increased. It therefore appears to be more desirable to vary the compensating effect of the phase advancer by increasing the resistance in the stator circuit beyond 0·25 ohm than by reducing it below 0·25 ohm.

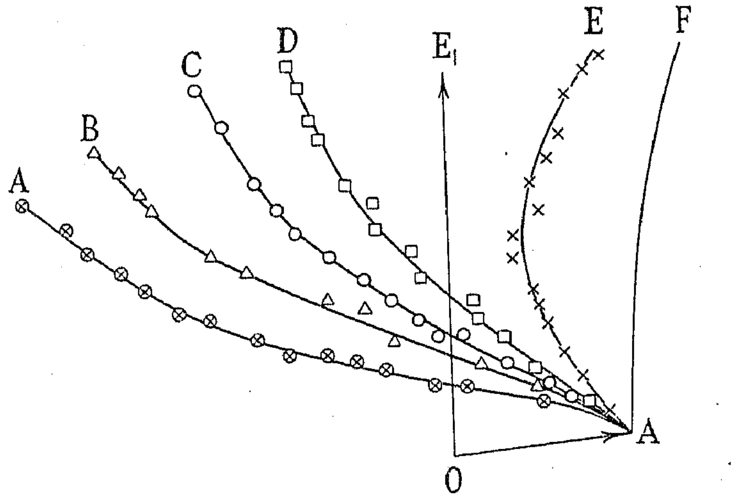

Fig. 6.—Current loci of a 7·5-h.p. induction motor connected to a separately-driven constant-speed Leblanc phase-advancer with stator winding.

Scale: 1 in. = 20 amperes.

A. External resistance in stator circuit = 0·24 ohm.
B. External resistance in stator circuit = 0·96 ohm.
C. External resistance in stator circuit = 3·34 ohms.
D. Stator winding open-circuited.
E. Stator winding short-circuited.
F. Uncompensated motor.

To study the effect of the additional winding on the rotor, the stator winding was open-circuited and the slip-ring winding was closed through a rheostat. The curves in Fig. 8 show the slip (s), the power factor ($\cos \phi_1$) of the motor, and the current (I_{SR}) in the slip-ring winding of the phase advancer, with a constant current of 20 amperes in the secondary of the motor and the various resistances (R') in the slip-ring winding circuit. The phase advancer was run at a constant speed of 750 r.p.m.

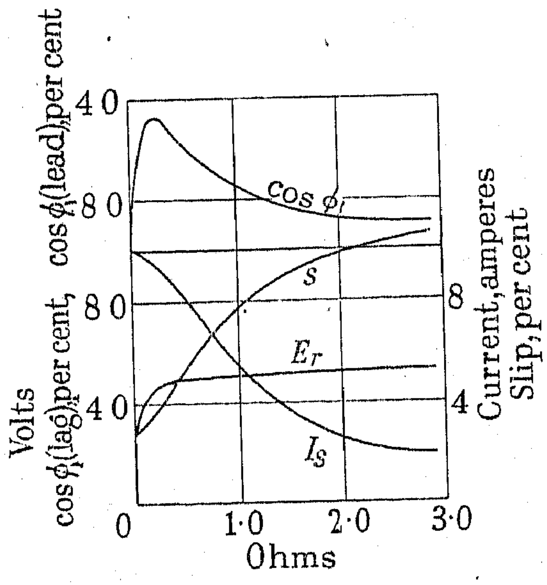

Fig. 7.—Curves showing the effect of inserting various resistances in the stator circuit of a phase advancer having a stator winding, with constant current of 35 amperes in the secondary of the 7·5-h.p. induction motor compensated by the phase advancer.

With the slip-ring winding open, the machine works as a standard Leblanc phase-advancer and $\cos \phi_1 = 1\cdot 0$ and $s = 8$ %. For $R' = 0$, $\cos \phi_1 = 0\cdot 77$ (lagging) and $s = 3\cdot 55$ %. For values of R' between 0 and 2·64 ohms, the power factor is lagging. The provision of an additional rotor winding thus reduces the compensating effect of the Leblanc phase-advancer, but enables the power factor to be varied between wide limits.

The conclusions from these tests are that by adding a stator winding or a rotor winding to the Leblanc phase-advancer the compensating effect of the phase advancer can be varied within wide limits, but the phase advancer with a stator winding is much better than that with an additional rotor winding, as the former provides much greater compensation than the latter.

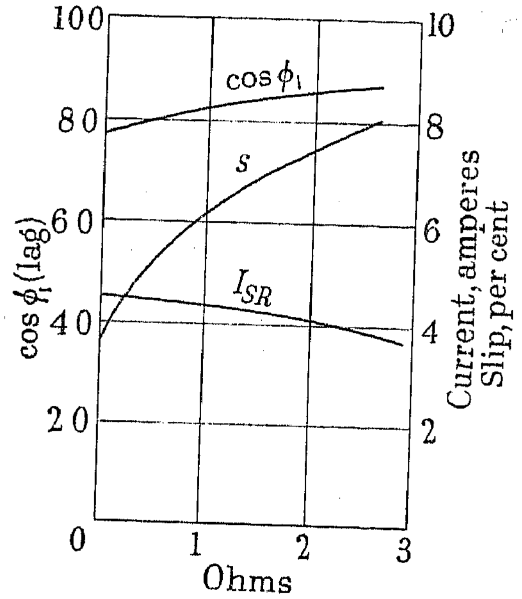

Fig. 8.—Curves showing the effect of inserting various resistances in the additional rotor winding of a phase advancer having an additional rotor winding, with constant current of 20 amperes in the secondary of the 7·5-h.p. induction motor compensated by the phase advancer.

(6) PRINCIPLE UNDERLYING ACTION OF LEBLANC PHASE-ADVANCER WITH A STATOR WINDING OR AN ADDITIONAL ROTOR WINDING

The important change in the characteristics of the Leblanc phase-advancer which a stator winding or an additional rotor winding produces is that the phase difference between the phase-advancer voltage and current is no longer constant at 90° as in the standard phase-advancer, but changes with the load on the motor. Before considering how and to what extent this change takes place, it is desirable to obtain some idea of the variation in the compensating effect of a given phase-advancer voltage, when its phase with respect to the phase-advancer current is altered.

Let us assume that we have a phase advancer capable of giving a constant voltage leading the current by any desired angle from 0 to 180°. Let OI_2 in Fig. 9 represent the direction of the current in the secondary of the induction motor, and OR the resistance drop in the secondary and the rotor of the phase advancer. With centre R and radius equal to the constant phase-advancer voltage, draw a circle LMNP. Then the semicircle LMN is the locus of the extremity of the phase-advancer induced voltage, and the semicircle NPL is the locus of the extremity of the voltage consumed by the phase-advancer induced voltage. Neglecting, for simplicity, all other voltage-drops in the secondary circuit of the motor, the semicircle NPL is also the locus of the extremity of the secondary voltage. Draw RP perpendicular to OR, cutting the circle at P. Draw RS making an angle greater than 90° with RO. Join OP, cutting the circle at Q. Join OS and RQ. Draw RY making an angle greater than $\angle ORQ$ but less than 90°, and let it cut OP and the circle at X and Y respectively. It will now be seen from the diagram that with a phase-advancer voltage equal to RP but leading the current by $\angle ORY$, the secondary current leads the secondary voltage by an angle $\angle YOR$ greater than $\angle POR$, the lead obtained with the standard Leblanc phase-advancer. It will also be seen that a lead of the secondary current equal to $\angle POR$ can be obtained by a voltage RX less than RP. Similarly it can be shown that with a phase-advancer voltage leading the current by an angle less than 90° but greater than $\angle ORQ$, a lead of the secondary current equal to or greater than $\angle ROP$ can be obtained with a smaller voltage than PR, the voltage required from a standard Leblanc phase-advancer. With the phase of the phase-advancer voltage greater than 90° or less than $\angle ORQ$, the compensating effect of the phase advancer is less than that of the standard Leblanc phase-advancer.

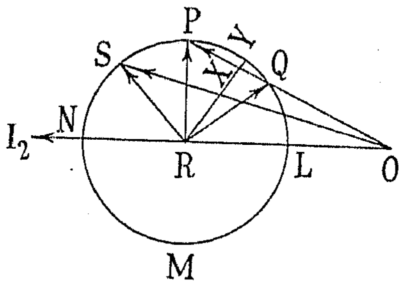

Fig. 9.—Vector diagram showing the effect of varying the phase of a given phase-advancer voltage.

(7) THEORY OF LEBLANC PHASE-ADVANCER WITH A STATOR AND A STATOR WINDING

It is usual to regard a phase advancer as a source of voltage, having a fixed phase relation with either the current or the voltage in the secondary of the motor it compensates. To understand the action of the Leblanc phase-advancer with a stator winding or an additional rotor winding, the broader conception of phase advancers which is outlined below is necessary. This conception can be applied to other phase advancers having more than one winding.

(a) Phase Advancer regarded as a Commutator Motor

If the Leblanc phase-advancer with stator winding shown in Fig. 3 is supplied with 3-phase currents at the commutator brushes and the stator winding is short-circuited, it will run as an induction motor and may be called a commutator motor. The induction motor to be compensated by the phase advancer will be referred to simply as an induction motor. The commutator winding is the primary and the stator winding the secondary of the commutator motor. The direction of rotation of the commutator motor is opposite to the direction of rotation of the rotating flux of the commutator winding.

An approximate vector diagram of the commutator motor is shown in Fig. 10. OA is the flux in the air-gap of the motor. OB is the magnetizing current of the motor, in phase with the flux, neglecting the iron losses. OC, lagging behind OA by 90°, is the direction of the voltage induced by the air-gap flux in the primary and the secondary of the commutator motor. The reactance of the secondary, being proportional to the slip of the motor, is small and may be neglected. Then the secondary current is in phase with OC. Let OD be the secondary current, reduced to primary, at any load. Then BE, equal and parallel to OD, is the component of the primary current required to overcome the ampere-turns of the secondary. OE is the total primary current. It will be observed that the voltage induced in the commutator winding lags behind the current in the commutator winding by 90° on open-circuit, and that the angle of lag increases with the load on the motor.

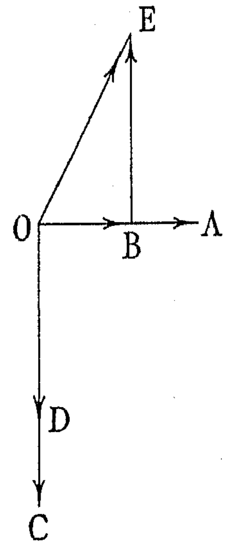

Fig. 10.—Approximate vector diagram of the Leblanc phase-advancer with stator winding, regarded as a commutator motor.

(b) Vector Diagram and Equations of the Commutator Motor used as a Phase Advancer

In dealing with an induction motor connected to a phase advancer, it is desirable to replace all closed windings in the motor and the phase advancer by equivalent star windings. This is easily done, merely by proceeding on the assumption that all the windings are star-connected. All the quantities relating to the induction motor and the phase advancer specified below, are per phase star and are reduced to the primary of the induction motor. The star values reduced to primary of the induction motor can be obtained as shown below. For example, the star values of the induction-motor secondary and the phase-advancer primary resistances are half the measured resistances between lines, multiplied by k_m^2, where k_m is the ratio of transformation of the induction motor. The star value of the resistance of the phase-advancer secondary is equal to half the measured resistance between lines, multiplied by $k_m^2 k_a^2$, where k_a is the ratio of transformation of the phase advancer regarded as a commutator induction motor.

When the commutator motor is working as a phase advancer, the rotor revolves in the same direction as the rotor flux and at a speed higher than that of the flux. In other words, the phase advancer is being driven as a generator, at a speed higher than that of its flux and in a direction opposite to that in which it tends to run as a motor. Assume that the phase advancer is driven at a constant speed; then, using the nomenclature given in the "List of Symbols" (see page 383), the rotor flux of the phase advancer cuts the rotor conductors at $(N_a - sN_s)$ or $N_s(c - s)$ r.p.m. and the stator conductors at sN_s r.p.m. The frequency of the current in the rotor conductors is $(c - s)f$ and that in the stator conductors is sf. Therefore, when the phase advancer is working the exciting reactance of its primary is $(c - s)x_0'$, the leakage reactance of its primary is $(c - s)x_1'$, and the leakage reactance of its secondary is sx_2'.

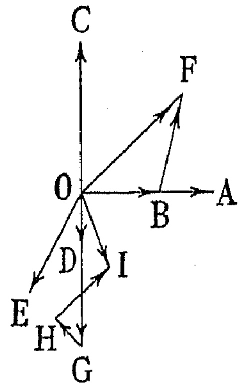

Fig. 11.—Vector diagram of Leblanc phase-advancer with stator winding.

$OA = \Phi'$, $OB = I_0'$, $OC = -E'$, $OD = sE'/(c - s)$, $OE = -I_2'$, $BF = I_2'$, $OF = I_1'$, $GH = j(c - s)x_1'I_1'$, $HI = r_1'I_1'$, $OE = E_1'$, $\underline{/COF} = \theta$.

Fig. 11 shows an approximate vector diagram of the phase advancer. $OA = \Phi'$ is the flux in the air-gap of the phase advancer; and $OB = I_0'$ is the exciting current of the phase advancer, in phase with the flux, neglecting the iron losses (for simplicity). The revolving flux in the primary of the phase advancer cuts the primary conductors at $(c - s)N_s$ r.p.m. Therefore, the voltage induced in the primary by the air-gap flux is

$$OC = -E' = j(c - s)x_0'I_0' \quad . \quad . \quad . \quad (1)$$

leading the flux by 90°.

The revolving flux of the primary of the phase advancer cuts the conductors of the secondary at sN_s r.p.m. Therefore, the voltage induced in the secondary is

$$OD = \frac{sE'}{c - s} \text{ lagging behind the flux by 90°.}$$

The current in the secondary of the phase advancer is

$$OE = -I_2' = \frac{sE'/(c - s)}{R_2' + jsx_2'} \quad . \quad . \quad . \quad (2)$$

$BF = I_2'$ is the component of the phase-advancer primary current required to overcome the ampere-turns of its secondary. The phase-advancer primary current is

$$\mathrm{OF} = I_1' = I_0' + I_2' \quad . \quad . \quad . \quad . \quad (3)$$

$\mathrm{OG} = E$ is the component of the primary impressed voltage E_1' consumed by the voltage induced in the primary by the air-gap flux. $\mathrm{GH} = j(c - s)x_1'I_1'$ is the voltage consumed by the leakage reactance of the primary, and $\mathrm{HI} = r_1'I_1'$ is the voltage consumed by the resistance of the primary. The primary impressed voltage is

$$\mathrm{OI} = E_1' = [r_1' + j(c - s)x_1']I_1' + E' \quad . \quad . \quad (4)$$

Substituting for I_0' and I_2' from (1) and (2) in (3), and substituting for E' from the resulting equation in (4),

$$E_1' = \left[r_1' + j(c-s)x_1' + \frac{1}{\dfrac{1}{-j(c-s)x_0'} + \dfrac{1}{-\dfrac{c-s}{s}(R_2' + jsx_2')}} \right] I_1' \quad . \quad . \quad . \quad (5)$$

The leakage reactances $(c - s)x_1'$ and sx_2' are small compared with the exciting reactance $(c - s)x_0'$ of the phase advancer and the leakage reactances of the induction motor, and may be neglected with a view to avoiding complications and obtaining a clearer physical conception of the phase advancer. Equation (5) now reduces to

$$E_1' = \left[r_1' + \frac{1}{\dfrac{1}{-j(c-s)x_0'} + \dfrac{1}{[-(c-s)R_2']/s}} \right] I_1' \quad (6)$$

It will be seen from equation (6) that the phase advancer is equivalent to an impedance consisting of a resistance r_1' in series with a negative reactance $-(c - s)x_0'$ and a negative resistance $[-(c - s)R_2']/s$ in parallel, as shown in Fig. 12(a). I_0' and I_2' are the currents in the branches of the parallel circuit and their resultant is I_1'.

The simplified vector diagram of the phase advancer is as shown in Fig. 12(b) and can be obtained with the help of the vector diagram in Fig. 11 or the equivalent circuit in Fig. 12(a). In the vector diagram, $\mathrm{OA} = \Phi'$, $\mathrm{OB} = I_0'$, $\mathrm{OC} = -E'$, $\mathrm{OD} = sE'/(c - s)$, $\mathrm{OE} = -I_2'$, $\mathrm{BF} = I_2'$, $\mathrm{OF} = I_1'$, $\mathrm{OG} = E'$, $\mathrm{GH} = r_1'I_1'$, and $\mathrm{OH} = E_1'$.

(c) Explanation of Test Results

An examination of the parallel circuit in Fig. 12(a) and the vector diagram in Fig. 12(b) shows that the voltage induced in the primary of the phase advancer leads the current in the primary of the phase advancer by an angle θ given by

$$\tan\theta = \frac{\mathrm{OB}}{\mathrm{BF}} = \frac{I_0'}{I_2'} = \frac{R_2'}{sx_0'} \quad . \quad . \quad . \quad (7)$$

Assuming the phase advancer to be unsaturated, x_0' is constant. It will now be seen from equation (7) that, with a given resistance R_2', θ is very nearly equal to 90° when the induction motor is running light, as the slip (s) of the motor is very small. As the slip, and consequently the load, of the motor increases, θ decreases, and the compensating effect of the phase advancer improves as explained with reference to Fig. 9, and is more than that of the phase advancer when used as a standard Leblanc phase-advancer. The smaller the value of R_2', the greater the decrease of θ, and the greater the compensating effect of the phase advancer as shown by the experimental current loci in Fig. 6. However, R_2' should not be reduced indefinitely, as θ might become too small and we might get the same condition as is shown in the diagram of Fig. 9 when θ was less than $\underline{/\mathrm{ORQ}}$. This actually appears to be the case when the secondary is short-circuited, and explains the poor compensating effect of the phase advancer shown by the current locus E in Fig. 6.

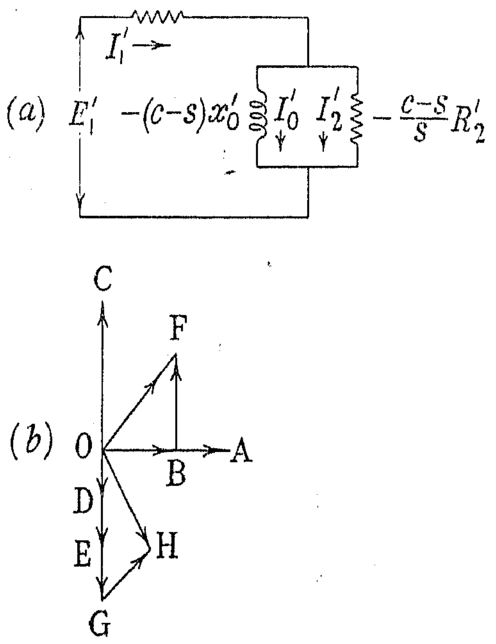

Fig. 12.—Simplified (a) equivalent circuit and (b) vector diagram of Leblanc phase-advancer with stator winding.

$\mathrm{OA} = \Phi'$, $\mathrm{OB} = I_0'$, $\mathrm{OC} = -E'$, $\mathrm{OD} = sE'/(c - s)$, $\mathrm{OE} = -I_2'$, $\mathrm{BF} = I_2'$, $\mathrm{OF} = I_1'$, $\mathrm{GH} = r'I_1'$, $\mathrm{OH} = E_1'$, $\underline{/\mathrm{COF}} = \theta$.

The characteristics shown in Fig. 7 can also be explained with the help of equation (7). From this equation, we have

$$\frac{I_2'}{I_0'} = \frac{sx_0'}{R_2'}$$

Squaring both sides, adding 1 and simplifying,

$$\frac{I_0'^2 + I_2'^2}{I_0'^2} = \frac{I_1'^2}{I_0'^2} = \frac{s^2x_0'^2 + R_2'^2}{R_2'^2} \quad . \quad . \quad . \quad (8)$$

For the values of R_2' used in the tests, and the slip observed, $s^2x_0'^2$ is small compared with $R_2'^2$, and I_0' is therefore very nearly equal to I_1'. This relation is independent of R_2' as long as R_2' is not comparable with sx_0'. Thus, at a constant phase-advancer primary current, the phase-advancer flux, and consequently the phase-advancer voltage, is very nearly constant. This explains the practically constant voltage observed in the slip-ring winding and shown by the curve E_r in Fig. 7. With constant phase-advancer current and induced voltage, and the phase of the phase-advancer voltage decreasing with increase of R_2', we have the conditions referred to in connection with the diagram in Fig. 9. Decrease in slip with decrease of R^2, increase in compensation with decrease of R_2' up to a point, and then decrease in compensation with further decrease of R_2', are what should be expected.

(8) THEORY OF INDUCTION MOTOR CONNECTED TO A SEPARATELY-DRIVEN CONSTANT-SPEED LEBLANC PHASE-ADVANCER WITH A STATOR AND A STATOR WINDING

(a) Equivalent Circuit of the Motor

The equation of the secondary of the induction motor is

$$-sE = -(r_2 + jsx_2)I_2 - E_1'$$

or

$$E = \left(\frac{r_2}{s} + jx_2\right)I_2 + \frac{E_1'}{s} \quad . \quad . \quad . \quad (9)$$

Substituting for E_1' from (6) in (9), and putting $I_1' = -I_2$,

$$E = \left\{\left(\frac{r_2}{s} + jx_2\right) + \frac{r_1'}{s} + \frac{1}{\dfrac{1}{\dfrac{-j(c-s)}{s}x_0'} + \dfrac{1}{\dfrac{(c-s)}{s^2}R_2'}}\right\}I_2 \quad . \quad . \quad . \quad (10)$$

The equivalent circuit of the induction motor with the phase advancer is obtained from the well-known equivalent circuit of the uncompensated induction motor by replacing the impedance

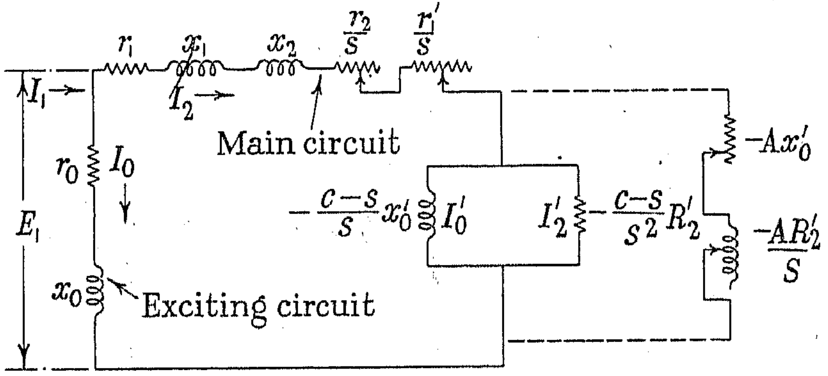

Fig. 13.—Equivalent circuit of an induction motor connected to a separately driven, constant-speed Leblanc phase-advancer with stator winding.

$$\frac{r_2}{s} + jx_2$$

in it by the coefficient of I_2 in equation (10). The equivalent circuit is shown in Fig. 13. For convenience in calculations, it is desirable to replace the parallel impedances in the secondary circuit by their joint impedance

$$-Ax_0' + \frac{-jAR_2'}{s}$$

as shown by the dotted lines in Fig. 13; where

$$A = \frac{(c-s)}{s} \cdot \frac{x_0'R_2'/s}{(R_2'/s)^2 + x_0'^2}$$

$$= \frac{(c-s)}{s}\cos\theta\sin\theta \quad . \quad . \quad . \quad . \quad (11)$$

[from equation (7)]

The two branches of the final equivalent circuit are called the exciting circuit and the main circuit, as indicated.

(b) Current locus of the Motor with Unsaturated Phase-advancer

Fig. 14 shows the vector diagram of the motor. In this diagram,

OE represents the direction of the primary impressed voltage (E_1);
ON ($= I_0$) is the exciting current of the motor;
NX and NY are the axes of co-ordinates, perpendicular and parallel, respectively, to OE;
NP ($= I_2$) is the current in the main circuit;
(x, y) are the co-ordinates of P referred to N as origin;
$\underline{/YNP}$ ($= \psi$) is the phase difference between E_1 and I_2;
$\underline{/EOP}$ ($= \phi_1$) is the phase difference between E_1 and I_1;
$\underline{/EON}$ ($= \phi_0$) is the phase difference between E_1 and I_0.

Let R = resistance of the main circuit, X = reactance of the main circuit, Z = impedance of the main circuit $= \sqrt{(X^2 + Y^2)}$ and $R_2 = r_2 + r_1'$. Then

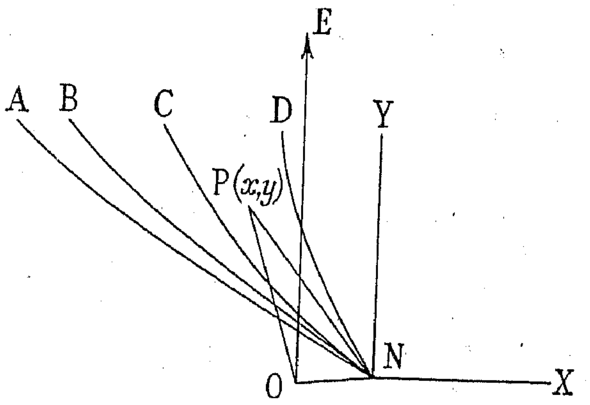

Fig. 14.—Theoretical current loci of a 150-h.p. induction motor with constant-speed Leblanc phase-advancers with stator winding and additional rotor winding.

Scale: 1 cm. = 20 amperes.
A. Resistance in stator circuit of phase advancer = 0·1 ohm.
B. Resistance in stator circuit of phase advancer = 0·2 ohm.
C. Stator winding open-circuited.
D. Resistance in additional rotor winding of phase advancer = 2·0 ohms.

$$R = \frac{yE_1}{x^2 + y^2} = r_1 + \frac{R_2}{s} - Ax_0' \quad . \quad . \quad (12)$$

$$X = \frac{xE_1}{x^2 + y^2} = x_1 + x_2 - \frac{AR_2}{s} \quad . \quad . \quad (13)$$

In equations (12) and (13), R_2 is variable owing to the contact resistance of the brushes in the secondary circuit of the motor, and x_0' is variable owing to saturation of the phase advancer. For simplicity, R_2 may be regarded as constant at a suitable mean value, and x_0' may be regarded as constant by assuming the phase advancer to be unsaturated. Then, one way of obtaining an equation for the locus of current in the main circuit is to eliminate s between equations (12) and (13), remembering that A contains s and s^2. But the equation of the locus thus obtained would be very complex and only of academic interest. A simpler equation of the locus is obtained if terms involving s^2 in equations (12) and (13) are neglected, but this equation is found to be of the fourth degree, and does not appear to be of any practical use.

The simplest and most useful way to proceed is to work, point by point, with the help of equations (12) and (13), as shown below, with reference to a 150-h.p., 2 000-volt, 50-cycle, 600-r.p.m. induction motor of the following constants: $E_1 = 1\ 155$ volts, $I_0 = 15$ amperes, $\cos\phi_0 = 0\cdot 1$, $r_1 = 0\cdot 63$ ohm, $r_2 = 0\cdot 65$ ohm, $x_1 = 3\cdot 48$ ohms, and $x_2 = 2\cdot 1$ ohms. For the phase advancer, $r'_1 = 0\cdot 13$ ohm (20 % of r_2), $x'_0 = 1\cdot 1$ ohm, and $R'_2 = 0\cdot 1$ ohm. The phase advancer is driven separately at a constant speed N_s.

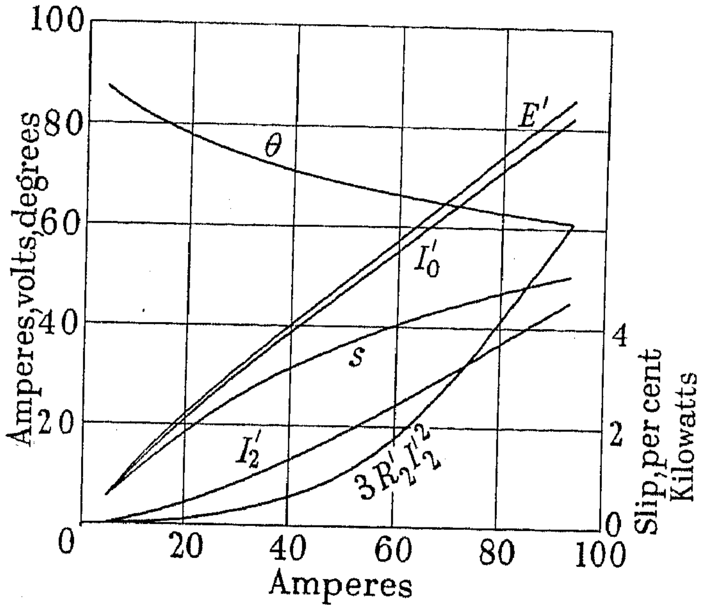

Fig. 15.—Characteristics of a Leblanc phase-advancer with stator winding connected to a 150-h.p. induction motor.

Assume any value of slip, say $s = 0\cdot 02$. Substituting for s in equations (12) and (13), we get $R = 28\cdot 3$, $X = -\ 45\cdot 8$, $Z = 53\cdot 8$, $I_2 = E_1/Z = 21\cdot 5$, $I_2 \cos\psi = I_2R/Z = 11\cdot 3$, and $I_2 \sin\psi = I_2X/Z = -\ 18\cdot 3$; also

$$I_1 \cos\phi_1 = I_2 \cos\psi + I_0 \cos\phi_0 = 12\cdot 8$$

$$I_1 \sin\phi_1 = I_2 \sin\psi + I_2 \sin\phi_0 = -\ 3\cdot 3$$

$$I_1 = \sqrt{[(I_1 \cos\phi_1)^2 + (I_1 \sin\phi_1)^2]} = 13\cdot 2$$

$$\cos\phi_1 = (I_2 \cos\psi + I_2 \cos\phi_0)/I_1 = 0\cdot 97 \text{ (leading)}$$

The extremity of I_1 can now be plotted. Proceeding in this manner with various values of s, the entire current locus can be obtained. Curves A and B in Fig. 14 are the loci of the primary current of the motor for values of resistance (R_2) equal to $0\cdot 1$ ohm and $0\cdot 2$ ohm respectively, in the secondary circuit of the phase advancer. Curve C is the current locus with the stator winding open, i.e. with the machine used as a standard Leblanc phase-advancer.

With the stator winding open, the magnitude of the voltage (E') induced in the phase-advancer rotor, for a current I_2 in the secondary of the motor, is $(1 - s)x'_0I_2$, leading the current by 90°. With the stator winding closed through a resistance, the voltage induced in the phase-advancer rotor, for the same value of I_2, is $(1 - s)x'_0I'_0$. The difference between the voltages induced in the two cases is not much, because, in the working range of the motor, I'_0 is not much less than I_2, and the slip with the stator winding closed is less than that with the stator winding open. For example, consider a phase advancer operating in conjunction with a 150-h.p. motor; the slip at $I_2 = 40$ amperes is 4 %, and E' is 42·3 volts, when the stator winding of the phase advancer is open. With the stator winding closed and $R'_2 = 0\cdot 1$, $s = 3\cdot 2$ % and $E' = 40$ volts at the same value of I_2. Even though the voltage is less, its compensating effect is more, as it is acting at an angle arc tan $R'_2/(sx'_0) = 70°$ instead of 90°.

The curves in Fig. 15 show the variations of I'_0, I'_2, E', s and θ for various values of I_2 in the phase advancer of the 150-h.p. motor with the stator of the phase advancer closed and $R'_2 = 0\cdot 1$ ohm. It is interesting to note the variations of θ.

The copper loss ($3R'_2I'^2_2$) in the stator circuit of the phase advancer is also shown. If the power factor corresponding to any value of I_2 had been obtained with a standard Leblanc phase-advancer, this loss would have been avoided, but the voltage required from the standard Leblanc phase-advancer, and consequently its kVA, would be considerably greater than that of the phase advancer with stator winding.

(c) Predetermination of Performance Curves

The performance curves can be obtained as shown below with reference to the 150-h.p. motor with phase-advancer stator winding closed and $R'_2 = 0\cdot 1$. Assuming the value of slip (s) to be $0\cdot 02$, we obtain, as shown above, $I_2 = 21\cdot 5$, $I_1 = 13\cdot 2$, $\cos\psi = 0\cdot 525$, and $\cos\phi = 0\cdot 97$ (leading). Also $\theta = \text{arc tan}\, R'_2/(sx'_0) = 77\cdot 6°$, $I'_0 = I_2 \sin\theta = 21$, and $I_2 = I_2 \cos\theta = 4\cdot 6$. The output per phase is given by

$$E_1I_2 \cos\psi - (r_1 + R_2)I_2^2 - R'_2I'^2_2 = 12\cdot 35 \text{ kW}$$

The brake horse-power is 49·5.

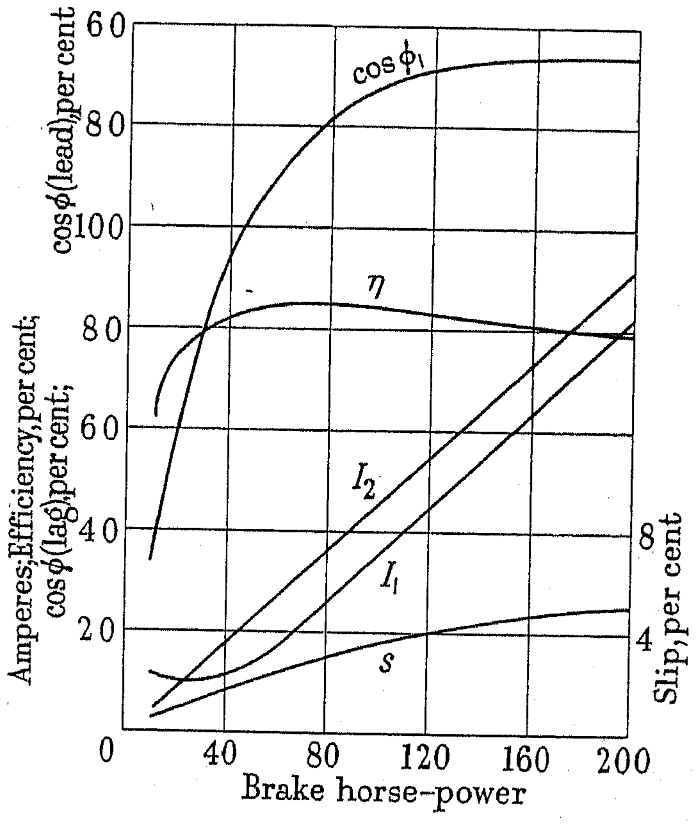

Fig. 16.—Theoretical performance curves of a 150-h.p. induction motor connected to a constant-speed Leblanc phase-advancer with stator winding.

The input per phase is given by

$$E_1I_2 \cos\psi + E_1I_0 \cos\phi_0 = 14\cdot 74 \text{ kW}$$

and $\eta = 84$ %. Proceeding in this manner with various values of s, the performance curves shown in Fig. 16 are obtained. The calculated performance curves of the motor when the phase-advancer stator winding is open, i.e. when it is working as a standard Leblanc phase-advancer, are shown in Fig. 17 for comparison.

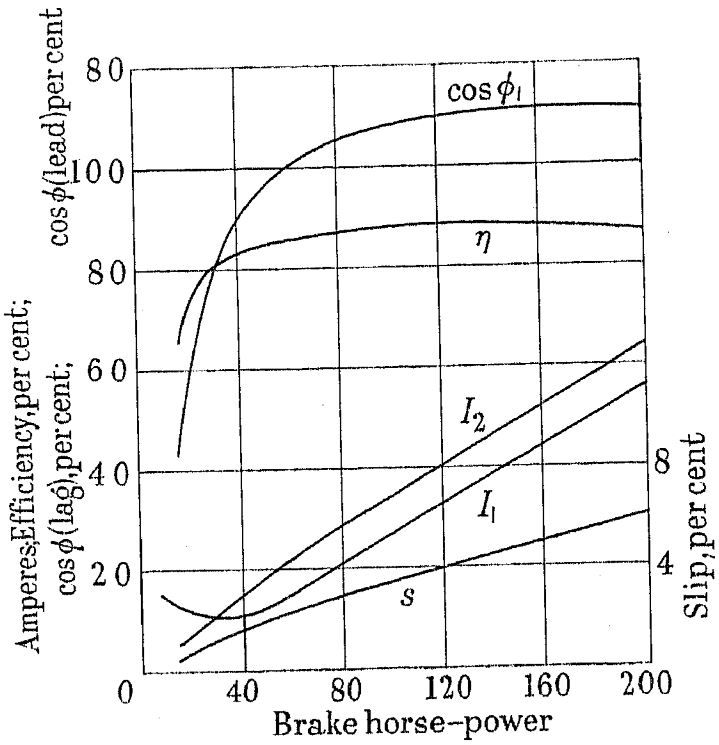

Fig. 17.—Theoretical performance curves of a 150-h.p. induction motor connected to a constant-speed Leblanc phase-advancer with stator winding, when the stator winding is open-circuited.

(d) Current Locus and Performance Curves of the Motor with Saturated Phase-advancer

In a practical phase-advancer, R_2 and x'_0 vary considerably with I_2, the former owing to the contact resistance of the brushes and the latter owing to saturation of the phase advancer. The procedure for predetermining the performance in this case is as follows: Assume a value of slip. Determine R_2 and x'_0 by assuming any value of I_2. Substituting these values of R_2 and x'_0 in equations (12) and (13), determine the value of I_2. This value of I_2 is near the correct figure at the assumed slip. Find R_2 and x'_0 at this value of I_2, and calculate I_2 again with the help of equations (12) and (13). This value of I_2 is very nearly the correct value of I_2 at the assumed slip. I_1, $\cos\phi_1$, the output, etc., can be determined as shown above. Proceeding in this manner with various values of slip, the current locus and performance curves can be obtained.

(9) THEORY OF SEPARATELY-DRIVEN CONSTANT-SPEED LEBLANC PHASE-ADVANCER WITH AN ADDITIONAL ROTOR WINDING

(a) Vector Diagram of the Phase Advancer

Fig. 4 shows a diagrammatic sketch of a 2-pole Leblanc phase-advancer with an additional rotor winding. The slip-ring winding is connected to a rheostat through a switch. The brushes on the commutator are connected to the secondary of the induction motor in such a way that the rotating flux, set up in the commutator winding by the secondary currents, revolves in the same direction as the phase advancer.

Let the phase advancer be driven at a constant speed $N_a = cN_s$, where N_s and c have the same significance as in the phase advancer with a stator winding. The rotating flux of the commutator winding cuts the conductors of the commutator and slip-ring windings at the same speed, namely $(c - s)N_s$ r.p.m. The frequency of the current and the induced voltage in the conductors is therefore the same for both windings and equal to $(c - s)f$ cycles per sec. The phase advancer may therefore be regarded as a transformer, of which the commutator winding is the primary and the slip-ring winding the secondary.

Let the symbols E'_1, E', I'_0, I'_1, I'_2, x'_0, r'_1, x'_1, x'_2, and R'_2 have the same significance with reference to the primary and secondary of this phase advancer as they had with the phase advancer with stator winding. When the phase advancer is working, the leakage reactances of its primary and secondary are $(c - s)x'_1$ and $(c - s)x'_2$ respectively. These reactances together with the iron losses of the phase advancer may be neglected for the same reasons as with the phase advancer having a stator winding. The vector diagram of the phase advancer is then as shown in Fig. 18(*a*).

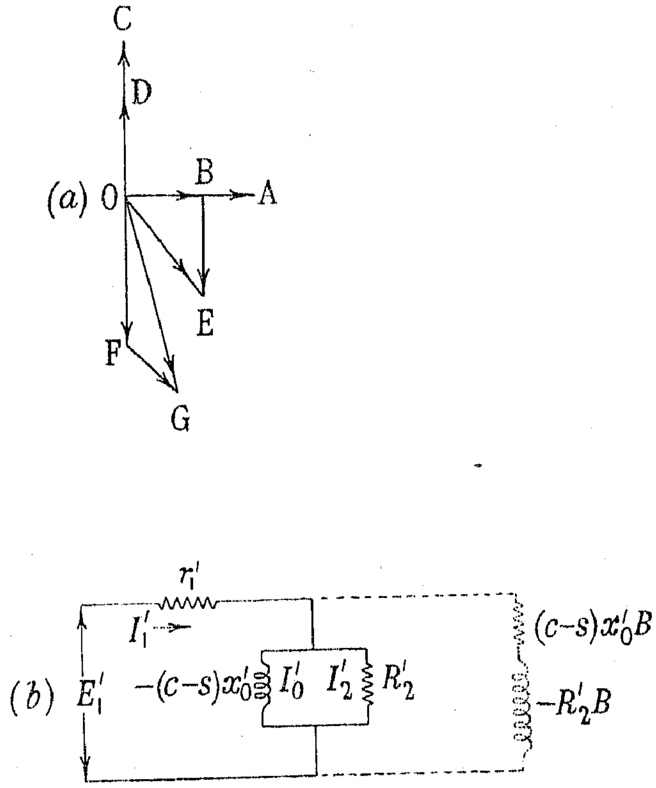

Fig. 18.—Simplified (*a*) vector diagram and (*b*) equivalent circuit of Leblanc phase-advancer with additional rotor winding.

$OA = \Phi'$, $OB = I'_0$, $OC = -E'$, $OD = -I'_2$, $BE = I'_2$, $OE = I'$, $OF = E'$, $FG = r'I'_1$, $OG = E'_1$, $\underline{/COE} = \theta$, $\underline{/FOE} = \theta'$.

$OA = \Phi'$ is the flux in the air-gap of the phase advancer;

$OB = I'_0$ is the magnetizing current, in phase with the flux, neglecting the iron losses;

$OC = -E' = j(c - s)x'_0I'_0$ is the voltage induced in the commutator winding;

$=$ voltage induced in the slip-ring winding, reduced to the primary of the phase advancer;

OD $= -I'_2 = -E'/R'_2$ is the current in the slip-ring winding;

BE $= I'_2$ is the component of the commutator-winding current required to overcome the ampere-turns of the slip-ring winding;

OE $= I'_1 = I'_0 + I'_2$ is the current in the commutator winding;

OE $= E'$ is the component of the phase-advancer primary impressed voltage required to overcome the voltage induced in the commutator winding by the air-gap flux;

FG $= r'_1 I'_1$ is the resistance drop in the commutator winding;

OG $= E'_1 = r'_1 I'_1 + E'$ is the voltage impressed on the commutator winding.

(b) Explanation of Test Results

It will be seen from the vector diagram that OC, the voltage induced in the phase advancer, leads I'_1, the phase-advancer current, by an angle $\theta = (\pi - \theta')$, where θ' is given by

$$\tan\theta' = \frac{I'_0}{I'_2} = \frac{R'_2}{(c-s)x'_0} \quad . \quad . \quad . \quad (14)$$

θ is greater than 90° and increases as I'_1 (the phase-advancer current) increases; or, in other words, as the load on the induction motor increases. θ being greater than 90°, the compensating effect of this phase advancer is less than that of the standard Leblanc phase-advancer, as can be seen with the help of Fig. 9. The poor compensating effect of the phase advancer and the large slip, as shown by the test curves in Fig. 8, can now be explained.

(c) Equivalent Circuit of Phase Advancer

The equivalent circuit of the phase advancer can be obtained in the same way as in the case of the phase advancer with stator winding. The equivalent circuit is shown in Fig. 18(*b*) and consists of a resistance r'_1 in series with a negative reactance $-(c-s)x'_0$ and a positive resistance R'_2 in parallel. For convenience in calculations, it is desirable to replace the parallel impedances by their joint impedance

$$(c-s)x'_0B - jR'_2B$$

as shown by dotted lines. B is given by

$$B = \frac{(c-s)x'_0R'_2}{R'^2_2 + (c-s)^2x'^2_0}$$
$$= \sin\theta'\cos\theta' \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

(10) THEORY OF INDUCTION MOTOR CONNECTED TO A SEPARATELY-DRIVEN CONSTANT-SPEED LEBLANC PHASE-ADVANCER WITH ADDITIONAL ROTOR WINDING

(a) Equivalent Circuit of Motor

The equivalent circuit of the induction motor and the phase advancer is shown in Fig. 19 and is obtained by inserting in the equivalent circuit of the induction motor the equivalent impedance of the phase advancer given in Fig. 18(*b*). The two branches of the equivalent circuit are called the main circuit and the exciting circuit, as shown in Fig. 19.

(b) Current Locus of Motor

Let $R_2 = r'_1 + r_2$. Then the resistance R and the reactance X of the main circuit are given by

$$R = r_1 + \frac{R_2}{s} + \frac{B(c-s)x'_0}{s} \quad . \quad . \quad . \quad (16)$$

$$X = x_1 + x_2 - \frac{BR'_2}{s} \quad . \quad . \quad . \quad . \quad (17)$$

The current locus of the motor can be obtained, point by point, with the help of equations (16) and (17), by proceeding as in the case of the phase advancer with stator winding. Curve D in Fig. 14 is the current locus of the 150-h.p. motor with the phase advancer running at a constant speed equal to N_s r.p.m., and $R'_2 = 2\cdot0$ ohms. The phase advancer is assumed to be unsaturated and x'_0 and R_2 have the same values as in a phase advancer with stator winding.

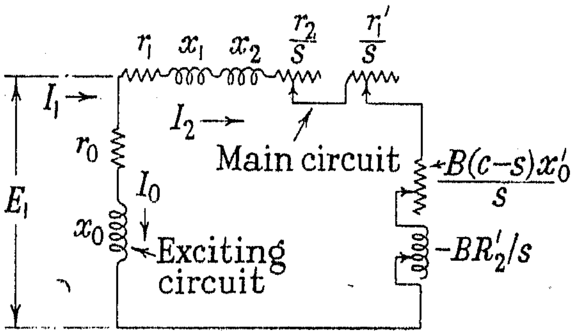

Fig. 19.—Equivalent circuit of an induction motor connected to a constant-speed Leblanc phase-advancer with additional rotor winding.

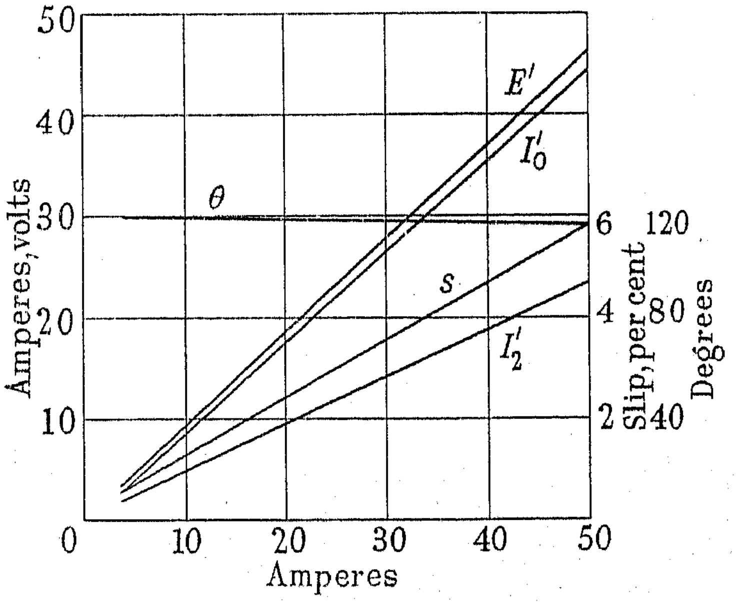

Fig. 20.—Theoretical characteristics of a Leblanc phase-advancer with additional rotor winding when connected to a 150-h.p. induction motor.

The curves in Fig. 20 show the calculated slip of the 150-h.p. motor and the values of E', I'_0, I'_2, and θ for the phase advancer, at various values of I_2. The phase-advancer speed is assumed to be equal to N_s r.p.m., and

$R_2' = 2\cdot 0$ ohms. It is interesting to note that θ varies from 120° at $I_2 = 4$ amperes to 118° at $I_2 = 50$ amperes, and may be regarded as constant. The value of θ depends on R_2', c, and x_0', and in the case of a given phase advancer running at a constant speed it can be changed by varying R_2'.

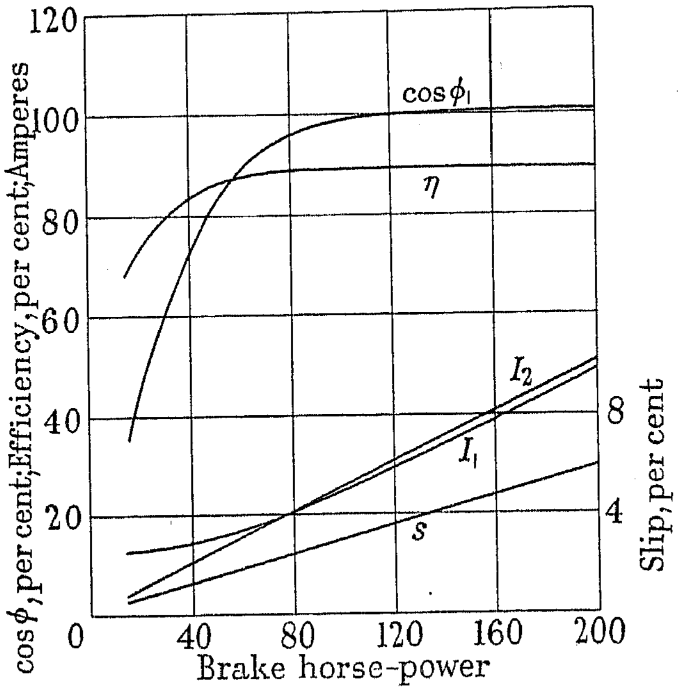

Fig. 21.—Theoretical performance curves of a 150-h.p. induction motor connected to a phase advancer with additional rotor winding.

(c) Predetermination of Performance Curves of Motor

The performance curves of the motor can be predetermined in the same way as was shown in connection with the phase advancer having a stator winding. Fig. 21 shows the calculated performance curves of the 150-h.p. motor with the phase advancer running at N_s r.p.m. and with $R' = 2\cdot 0$ ohms.

(11) PREDETERMINATION OF THE PERFORMANCE OF THE MOTOR WHEN THE PHASE ADVANCER WITH A STATOR WINDING OR AN ADDITIONAL ROTOR WINDING IS COUPLED OR BELTED TO THE MOTOR

The current locus and performance curves of the motor when the phase advancer of either type is coupled or belted to the motor can be predetermined by proceeding in the way outlined above. The only difference will be in the expressions for the voltages induced in the phase-advancer windings.

(12) CONCLUSIONS

The phase advancer with stator winding and the phase advancer with additional rotor winding are both equivalent to the standard Leblanc phase-advancer, when their secondaries are open. Hence the D^2L of the phase advancer with stator winding or additional rotor winding is the same as that of the standard Leblanc phase-advancer of the same speed, reactance and current-carrying capacity. The addition of the stator winding to the Leblanc phase-advancer provides an easy means of varying the action of the phase advancer and enhances its compensating action very considerably. The addition of the rotor winding also provides an easy means of varying the action of the phase advancer but reduces the compensating action of the phase advancer. Hence the Leblanc phase-advancer with stator winding is better than that with additional rotor winding.

THE PERFORMANCE AND LIMITATIONS OF THE COMPENSATED LOOP DIRECTION-FINDER*

By R. H. BARFIELD, D.Sc., Associate Member.

(*Paper received* 16*th August*, 1939.)

SUMMARY

The principle of both the single-dipole and double-dipole compensated loop direction-finder is described and reference is made to several patents which embody applications of these principles. A brief account is given of the theoretical and practical work carried out at Slough on the single-dipole system. It is shown that this system can in certain circumstances be made to have a considerably higher pick-up factor for a given overall area than the Adcock direction-finder but that it is limited to use on ground of good conductivity. The double-dipole system, on the other hand, is independent of ground conductivity but has no superiority over the " H " type of Adcock system as regards pick-up factor.

INTRODUCTION

The compensated loop direction-finder consists of a combination of a loop direction-finder and one or two horizontal aerials or dipoles, the combination being such that the effects of a horizontally polarized wave on the loop and on the aerial or aerials mutually cancel one another. The compensated loop direction-finder thus has two forms, which are referred to below as the single and double dipole types. Though it is simplest and adequate to consider only the single-loop rotating forms of these systems, either of them could be arranged as fixed-aerial systems in which two compensated loops are erected at right angles to one another with aural or visual indicating apparatus.

Such a system can only have a claim for development if it can be shown that it will possess an appreciably larger pick-up factor than an Adcock system of the same dimensions. From this point of view the single-dipole type is the most promising, since, as will be shown, the size of dipole required to compensate a given size of loop is less.

Both types have formed the subject of patent specifications.† The circuits proposed are shown in Figs. 1, 2, and 3. The arrangement developed at the Radio Research Station, Fig. 4, differs from each of these. It will be seen that the combination of aerial and loop is effected in a very simple way which analysis shows to be also at least as efficient as the others. The double-dipole loop is virtually a combination of a loop and an " H " Adcock which has been rotated in its own plane through 90° so that it responds only to horizontally polarized waves in such a way as to oppose and cancel the " pick-up " of the loop with respect to these waves.

The single-dipole loop can also be regarded as a combination of this kind. In this case, however, the Adcock part consists of the single dipole and its image in the reflecting surface of the ground beneath. Thus the effective Adcock-aerial spacing may be considerably greater than the actual dimensions of the system which is the cause of its greater efficiency.

The mode of action of the double dipole being the simpler of the two, it will be dealt with first.

DOUBLE-DIPOLE LOOP

Assuming horizontally-polarized waves and referring to the system illustrated in Fig. 4(*a*), it can be shown that with the method of coupling between the spaced aerials and loop therein depicted the effective e.m.f. induced by the latter in the loop circuit is exactly in anti-phase with that induced in the loop itself, provided that the dimensions of the system are small compared with the wavelength. Furthermore, it can be shown that there is one definite value of the coupling condenser, depending on the aerial and loop dimensions, for which the two effects are equal and opposite for all angles of incidence, all wavelengths, and all heights of the system above the ground. This has been verified by experiments.

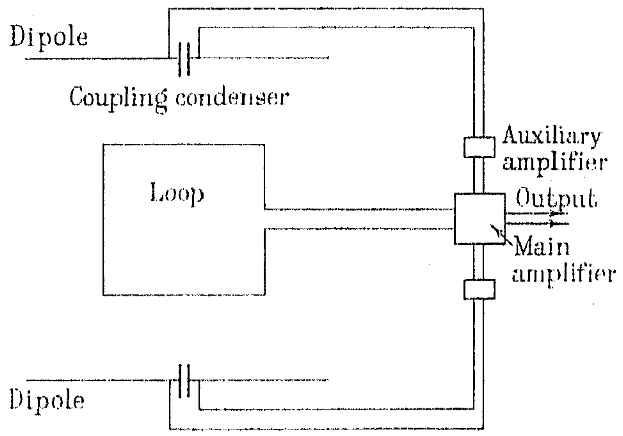

Fig. 1.—Lorenz circuit.

The pick-up factor of the double-dipole compensated loop is limited to that of the Adcock system which forms one of its component parts. It is clear, therefore, that it cannot be greatly superior, as regards pick-up factor, to a vertical-aerial Adcock system of the same dimensions. Nevertheless, there appeared at first some possibility that the mode of coupling of the dipoles to the receiver, which is inherent in the nature of the system and can be seen in Fig. 4(*a*), might be more effective than the twin-feeder arrangement usually adopted in the

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* Official communication from the National Physical Laboratory.

The Papers Committee invite written contributions, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Contributions (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† LORENZ: German Patent No. 624706—1934.
HELL: German Patent No. 601904—1933.
TELEFUNKEN: British Patent No. 464075—1937.

" H " type Adcock system. It was later realized, however, that whatever benefit is gained in this way can in fact be equally well taken advantage of by an Adcock system by introducing therein a similar form of coupling. For this reason it appears that the double-dipole compensated loop has no particular merit which makes its development worth while.

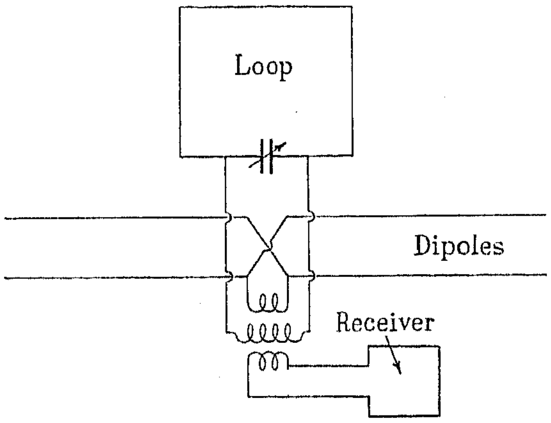

Fig. 2.—Circuit due to Dr. Hell.

SINGLE-DIPOLE LOOP

The single-dipole compensated loop works on the assumption that near the surface of ground of good conductivity the electric field of a horizontally polarized wave consists of co-phasal horizontal planes of zero intensity at the surface and increasing linearly with height for small fractions of a wavelength and for all angles of incidence. Under such conditions it can be shown that the e.m.f.'s induced in a loop and dipole at a fixed height maintain a constant amplitude and phase relationship for all angles of incidence and all wavelengths. This is the necessary and sufficient condition which allows the possibility of compensation (i.e. the cancellation of one e.m.f. by the other). Compensation is obtained, in the case of the single-dipole loop, when

$$\frac{\alpha h_1}{h_1 - h_2}\frac{a}{b} = \frac{C_A + C_B}{C_A} \quad . \quad . \quad . \quad . \quad (1)$$

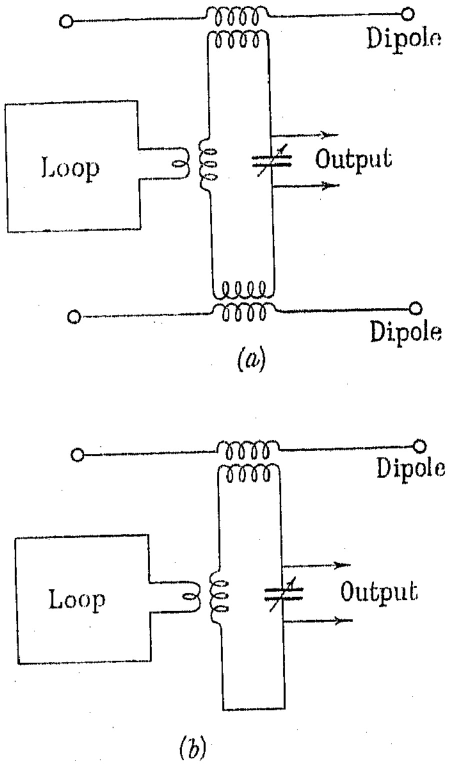

Fig. 3.—Telefunken circuit.

(a) Double dipole.
(b) Single dipole.

where h_1 = height of dipole and upper horizontal member of loop above ground; h_2 = height of lower horizontal member of loop; α = ratio $\frac{\text{effective length}}{\text{actual length}}$ of dipole; a = actual length of dipole; b = width of loop; C_A = capacitance of dipole; and C_B = capacitance of coupling condenser.

The practical success or failure of this type of compensated loop depends on how closely the working conditions permit the above assumptions to be made. The calculation of the residual polarization for a practical case is extremely complex. The approximate formula is

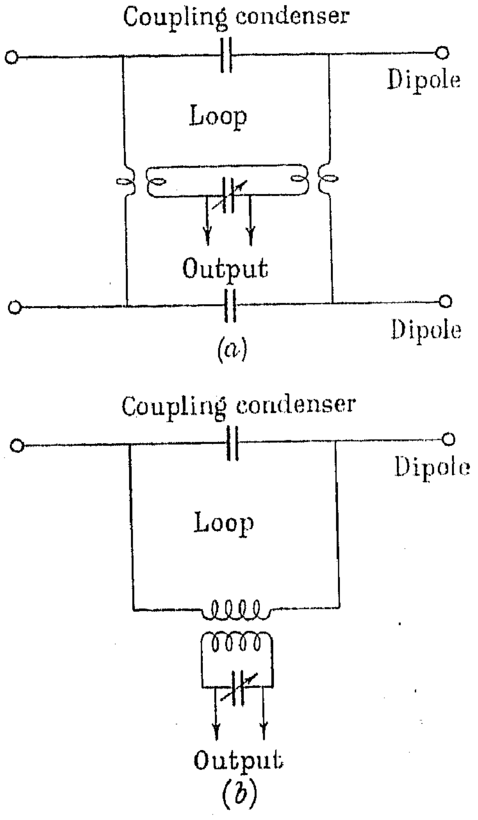

Fig. 4.—The author's circuit.

(a) Double dipole.
(b) Single dipole.

$$\tan \epsilon = \frac{\frac{b}{h}\left(Y_2 - \frac{h_2}{h_1}Y_1\right)}{\frac{2\pi b}{\lambda} Z \sin \theta}$$

where Y_1, Y_2 are the intensities of the horizontal fields at heights h_1, h_2; Z is the intensity of the vertical field; θ is the angle of incidence of the waves; and ϵ is the polarization error.

An evaluation of this formula gives, for ground of normal conductivity, the results shown in the Table (ϵ being the standard-wave error).

This performance is comparable with that of a medium or rather poor Adcock system.

The pick-up factor is easily obtainable; it is that of the loop part of the system, and is many times greater than that of an Adcock aerial of the same dimensions.

The single-dipole compensated loop thus constitutes a system of large polarization error but relatively high

Table

STANDARD-WAVE ERROR OF SINGLE-DIPOLE LOOP
For $\sigma = 1 \cdot 5 \times 10^8$ e.s.u.

λ	h_1/λ	$(h_1 - h_2)/\lambda$	ϵ
m.			deg.
1 000	0·01	0·005	20
1 000	0·03	0·005	11
1 000	0·03	0·03	8
300	0·035	0·033	12
300	0·1	0·1	4·5
30	0·1	0·1	12

pick-up factor; while the double-dipole compensated loop, on the other hand, is a system of poor pick-up factor and low polarization error. Both of them thus suffer from considerable disadvantages, though it is possible that the single-dipole type could be improved by artificially increasing the conductivity of the earth in its neighbourhood.

ACKNOWLEDGMENTS

The work was carried out as part of the programme of the Radio Research Board. A considerable part of the experimental work was carried out by Mr. B. Russell, whom the author wishes to thank for his assistance. The paper is published by permission of the Department of Scientific and Industrial Research.

INSTITUTION NOTES

I.E.E. MEETINGS FOR THE REMAINDER OF THE SESSION

The following Meetings have been arranged for April and May:—

Ordinary Meetings of The Institution

1940

11 Apr. J. W. GIBSON, M.Eng. "The High-Rupturing-Capacity Cartridge Fuse, with special reference to Short-Circuit Performance." (Illustrated by a cinematograph film.)

25 Apr. DR. C. G. DARWIN, M.C., F.R.S. The Thirty-First Kelvin Lecture. "Thermodynamics and the Coldest Temperatures."

9 May Annual General Meeting. (*Corporate Members and Associates only.*)

Meter and Instrument Section Meetings

5 Apr. J. L. CANDLER. "The Developments in Surge Recording by means of the Klydonograph." (E.R.A. Report.)

3 May H. WARREN. Lecture on "Insulation."

Transmission Section Meetings

10 Apr. P. M. HOGG, B.Sc. "The Development of a Pre-stressed ('Toughened') Glass Insulator."

E.R.A. Report on "The Performance of Glass Insulators and Comparisons with Porcelain." (To be presented by Mr. C. E. R. Bruce, M.A., B.Sc., and Dr. S. Whitehead, M.A.)

8 May M. C. HUNTER. "Mechanical Integrity in the Design of Electrical Circuit-Breakers."

Wireless Section Meetings

3 Apr. J. S. MCPETRIE, PH.D., D.Sc., and MISS A. C. STICKLAND, M.Sc. "Reflection Curves and Propagation Characteristics of Radio Waves along the Earth's Surface."

J. S. MCPETRIE, PH.D., D.Sc., and J. A. SAXTON, B.Sc. "An Experimental Investigation of Propagation of Radiation having Wavelengths of 2 and 3 Metres."

R. L. SMITH-ROSE, D.Sc., PH.D., and H. G. HOPKINS, PH.D., B.Sc. "Radio Direction-Finding on Wavelengths between 2 and 3 Metres (100 to 150 Mc./sec.)."

23 Apr. Informal Meeting.

1 May A. D. HODGSON. "Civil Air Transport Communication."

Informal Meetings

1 Apr. Discussion on "Electro-Acoustics in Practice." [Opened by Mr. P. G. A. H. Voigt, B.Sc. (Eng.).]

15 Apr. Discussion on "Adequate Domestic Equipment." (Opened by Mr. M. Whitgift.)

Overseas members can obtain advance copies of the above papers by applying to their Local Honorary Secretaries.

COMMUNICATIONS FROM OVERSEAS MEMBERS

Overseas members are especially invited to submit, for publication in the *Journal*, written communications on papers read before The Institution or published in the *Journal* without being read. The contributor's country of residence will be indicated in the *Journal*. In this connection a number of advance copies of all papers read before The Institution are sent to each Local Honorary Secretary abroad to enable him to supply copies to members likely to be in a position to submit communications.

VOLUNTARY NATIONAL SERVICE—CENTRAL REGISTER

Members are reminded that The Institution is anxious to keep the records of the above Register up to date, Any member who has been offered a position through the Register should therefore inform the Secretary of his decision, irrespective of whether the offer is accepted or refused.

All members who have volunteered for National Service should also notify the Secretary of any change in their employment, address, etc.

ENGINEERING JOINT COUNCIL

The Council of The Institution have nominated Dr. A. P. M. Fleming, C.B.E., M.Sc., Past-President, and Mr. H. T. Young, Past-President, as the two representatives—in addition to the President (*ex-officio*)—of The Institution on the Engineering Joint Council for the session 1940–1941.

NATIONAL REGISTER OF ELECTRICAL INSTALLATION CONTRACTORS

Mr. P. V. Hunter, C.B.E., Past-President, has been renominated by the Council as one of the representatives of The Institution on the Board of the above Register.

COUNCIL'S RULES FOR STUDENTS' SECTIONS

At their meeting on the 22nd February, 1940, the Council resolved that for the period of the war Rules 1 and 5 of the above should be modified as follows:—

Rule 1. The definition of a Graduate, which appears in this Rule, shall be amended by the deletion of the words " who is under 28 years of age."

Rule 5. Shall read as follows:—
AGE LIMIT.—The age limit for membership of a Section is normally 28 years, and Students shall cease to be members of a Section at the end of the calendar year in which they attain that age. During the period of the present hostilities Graduates attaining the age of 28 may, if they so wish, continue membership of a Section for the duration of the war and *ipso facto* become eligible for election or co-option for service on a Committee of a Section.

ASSOCIATE MEMBERSHIP EXAMINATION: NOVEMBER, 1939 (OVERSEAS CENTRES)

LIST OF SUCCESSFUL CANDIDATES WHO SAT IN BUENOS AIRES, CAIRO, HONG KONG, INDIA, IRAN, MALTA, NIGERIA AND SOUTH AFRICA

[Success in this Examination does not of itself constitute the candidate an Associate Member.]

Parts I and II *

Balasubramanian, Musiri Doraiswamy (*India*).
Benson, Cyril (*Iran*).
Bhat, Gurpur Srinivas (*India*).
Chappel, Mervyn Joseph William (*South Africa*).
Cousins, Norman James (*South Africa*).
Dandekar, Chintaman Damodar (*India*).
Das, Satyendra Prasanna (*India*).
De, Swayambhö Kumar (*India*).
Ghai, Manohar Lal (*India*).

Parts I and II—*continued.*

Ghazaros, Krikor (*Cairo*).
Greeff, Gabriel Jan Smuts (*South Africa*).
Halligey, Frederick Joseph (*South Africa*).
Holland, Herbert Roberts (*Buenos Aires*).
Hoon, Hari Krishen (*India*).
Jain, Uggar Sain (*India*).
Kaka, Barjor Jehangirjee (*India*).
Kanjilal, Sanat Kumar (*India*).
Kesavarao, Mysore Venkatasubbarao (*India*).
Kochak, Sharda Shanker (*India*).
Lahiri, Biswanath (*India*).
Mahindroo, Mulk Raj (*India*).
Marshall, Harry William Shury (*South Africa*).
Mascarenhas, Joseph Lawrence Patrick (*India*).
Meher-Homji, Jal Ardeshir (*India*).
Ng-Winglee, Cecil Raymond (*Hong Kong*).
Otto, Gert Petrus (*South Africa*).
Padia, Himmatlal Makanji (*India*).
Palmer, Frank Henry George (*Buenos Aires*).
Paramu, S. (*India*).
Parshad, Ram (*India*).
Patel, Shambhubhai Naranbhai (*India*).
Poacha, Savak Framroze (*India*).
Qureshi, Mumtaz Husain (*India*).
Raimondo, Anthony (*Malta*).
Rao, Penumarty Venkata Chalpaty (*India*).
Samsi, Ramesh Vithal (*India*).
Saxena, Sharda Charan (*India*).
Seshachar, Kolar Venkata (*India*).
Shah, Navnitlal Popatlal (*India*).
Shanmuganathan, V. S. (*India*).
Sharan, Swami (*India*).
Shrotri, Bhalchandra Mukund (*India*).
Shukla, Shankar Bapuji (*India*).
Smith, Ernest Leslie (*South Africa*).
Srinivasiengar, Kadaba Rangiengar (*India*).
Steele, Harry Theodore (*South Africa*).
Tonse, Surendranath Pai (*India*).
Umrigar, Dhanjisha Manekji (*India*).
Vajifdar, Maneck Bapuji (*India*).
Venkatvaradan, Bindingnavle Ramanna (*India*).
Watt, Arthur Muir (*South Africa*).

Part I only

Ahluwalia, Ugra Sen (*India*).
Ali, Syed Rauf (*India*).
Ananthanarayanan, M. R. (*India*).
Bendre, Shardchandra Shivram (*India*).
Bhaskare, Madhukar Balwant (*India*).
Bhide, Ramachandra Dattatraya (*India*).
Botha, Johannes Petrus Jacobus (*South Africa*).
Chowdhury, Jagadish Chandra (*India*).
Dandekar, Ramchandra Kashinath (*India*).
Date, Nilkantha Prabhakar (*India*).
Davies, William Griffith (*South Africa*).
Desai, Keshavlal Ambavidas (*India*).
Deshpande, Prabhakar (*India*).
Dey, Sukumar (*India*).
Dey, Sunil Kumar (*India*).
Giri, K. Periyaswamy (*India*).
Gupta, Bibhuti Bhushan (*India*).
Kagalwala, Abedin Fidahusein (*India*).

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* This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

Part I only—*continued.*

Kale, Mahadeo Ganesh (*India*).
Kinra, B. R. (*India*).
Krishna, Srinivas Muthu (*India*).
Mathews, John Alfred (*South Africa*).
Mehta, Dewan Singh (*India*).
Mukherjee, Haripada (*India*).
Murad, Yusufali Haji Mahomed (*India*).
Panicer, Kehar Singh (*India*).
Patrick, Roy Edwin (*South Africa*).
PrabhakaranNayar, Chandrasekharan Rajarajavarma (*India*).
Rao, P. Manmohan (*India*).
Shah, Muljeebhai Manilal (*India*).
Singh, Bhanu Pratap (*India*).
Vadgaokar, Manohar Ganpatrao (*India*).
Vaidyanathan, Kumarapalayam Ramasubramanyam (*India*).
Zaidi, S. Nasir Husain (*India*).

Part II only

Bhakat, Bhabani Prosad (*India*).
Chandra, Jaya (*India*).
Coker, Oluwaji Oladotun (*Nigeria*).
Gupte, Madhukar Shankar (*India*).
Kane, Robert Wotherspoon (*South Africa*).
Kapur, Ram Parkash (*India*).
Khan, Mohammad Akram (*India*).
Khasnis, Vasant Vinayakrao (*India*).
Krishnamurthi, Vaidyanath (*India*).
Lima, Louis Francis (*India*).
Lobo, George (*India*).
Mahill, Jagat Singh (*India*).
Narasingham, C. R. (*India*).
Sadiq, Syed Abdul (*India*).
Singh, Kartar (*India*).

A supplementary list of candidates who sat in Australia, Ceylon, New Zealand, Shanghai and Singapore will be published later.

TRANSFERS

The following transfers were effected by the Council at their meeting held on the 7th March:—

Student to Graduate

Annable, John Arthur, B.Eng.
Arcus, Geoffrey William, B.Sc.(Eng.).
Arundell, Edward Periam, B.Sc.
Buxton, Harry Livesay.
Cooper, William Burnett, B.Eng.
Dalaya, Tikaram Laxman, B.Sc.(Eng.).
Dalzell-Smith, Peter Edward.
Davey, Kendall Claude.
Dean, Gordon Stewart H.
Drury, James.
Gordon, Albert Percival, B.Sc.Tech.
Inman, John Douglas.
Johnson, Arthur Basil, B.Sc.(Eng.).
Johnstone, Wilfred Gordon, B.E.
Jones, David Gower, B.Sc.(Eng.).
Lees, John Reginald.
Midgley, David.
Monkhouse, Halton Hodgson, B.Sc.
Nicholas, Ronald Frank.
O'Hare, Michael Daniel.
Oliver, Robert, B.Sc. (Eng.).
Osborne, Kenneth William, B.Sc.
Parsons, Sydney John, B.Sc.
Phethean, John Forshaw.
Rockingham, Raymond Furneaux.
Rushton, Harry Leslie, B.Sc.
Sowood, Robert Collon, B.Sc.Tech.
Sperring, Francis Edwin, B.Sc.
Taylor, Leslie, B.Sc.
Trivett, Oscar Edward.
Usher, Eric Frederick F.W.
Wadely, Michael.
Winter, Francis Bernard B.

Hewittic Rectifiers

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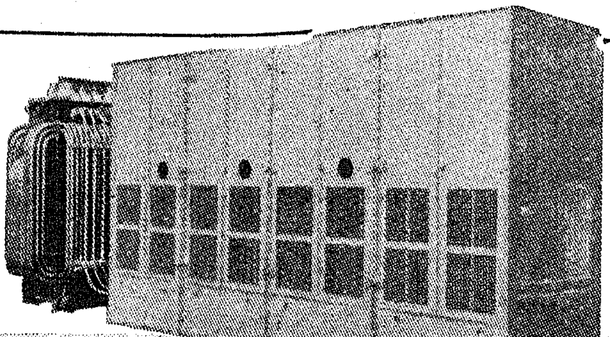

(Right) A typical Hewittic equipment, showing its sectionalised unit construction.

Trams and trolley-buses, involving the use of home produced fuel instead of imported petrol, are making an important contribution to the Nation's war economy. Hewittic rectifiers play a prominent part in this national service since **over 80 % of the rectifiers supplying these vehicles in Great Britain are Hewittic Rectifiers** which contribute still further to economy by their higher efficiency at all loads and the fact that, due to their great simplicity and reliability **they require no attention.**

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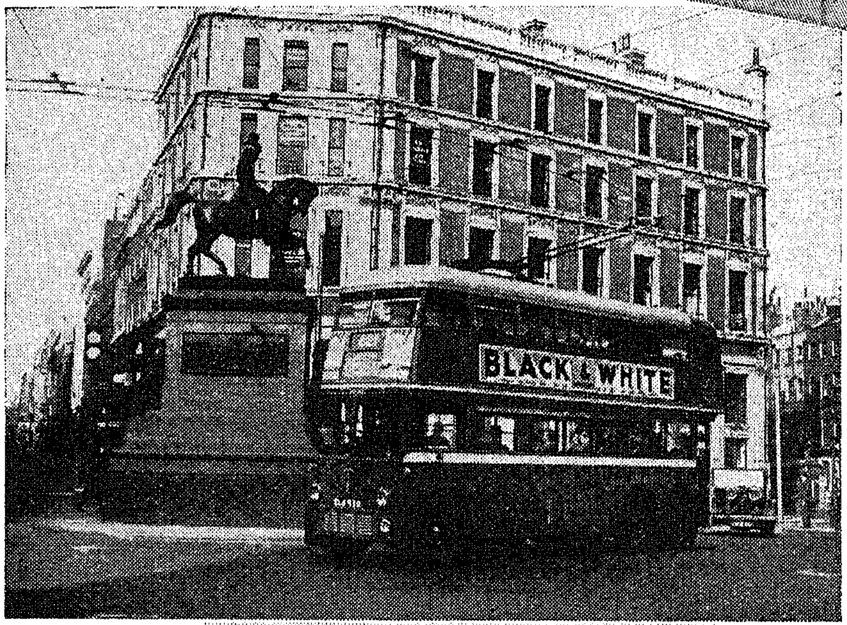

Photo by courtesy of Sunbeam Commercial Vehicles Ltd.

Photo by courtesy of Karrier Motors

Hewittic-supplied trolley-buses in London (top); Bradford (centre); and Bournemouth (right).

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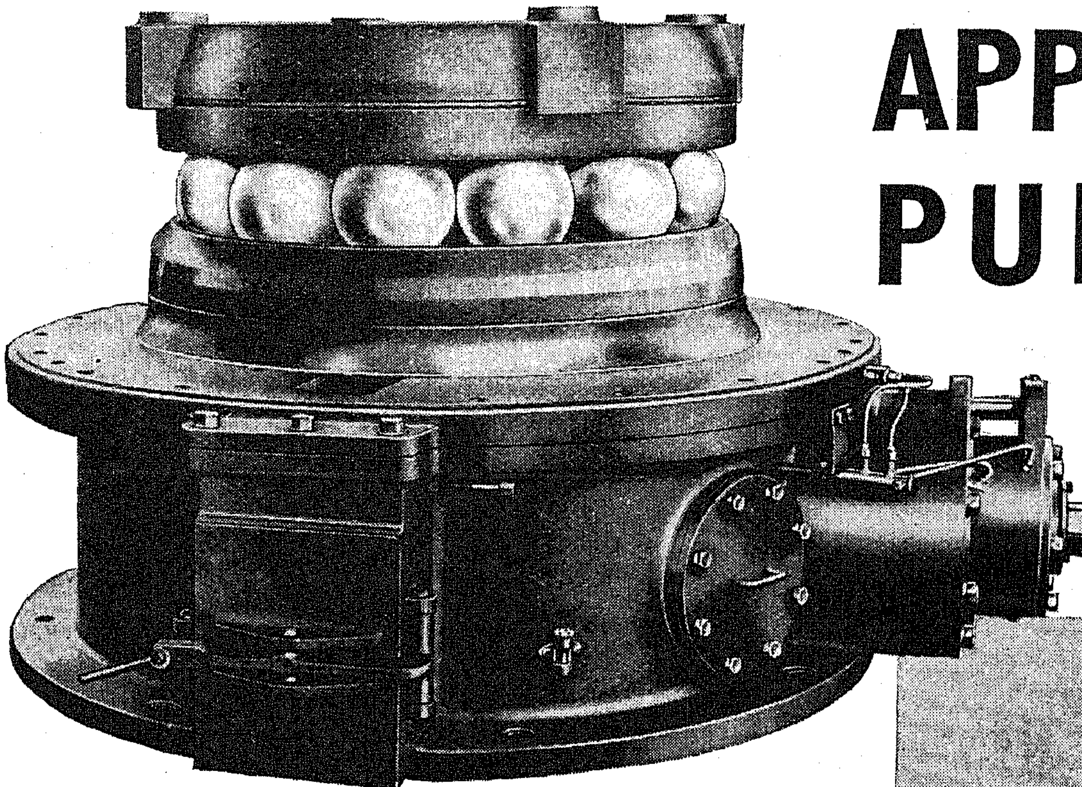

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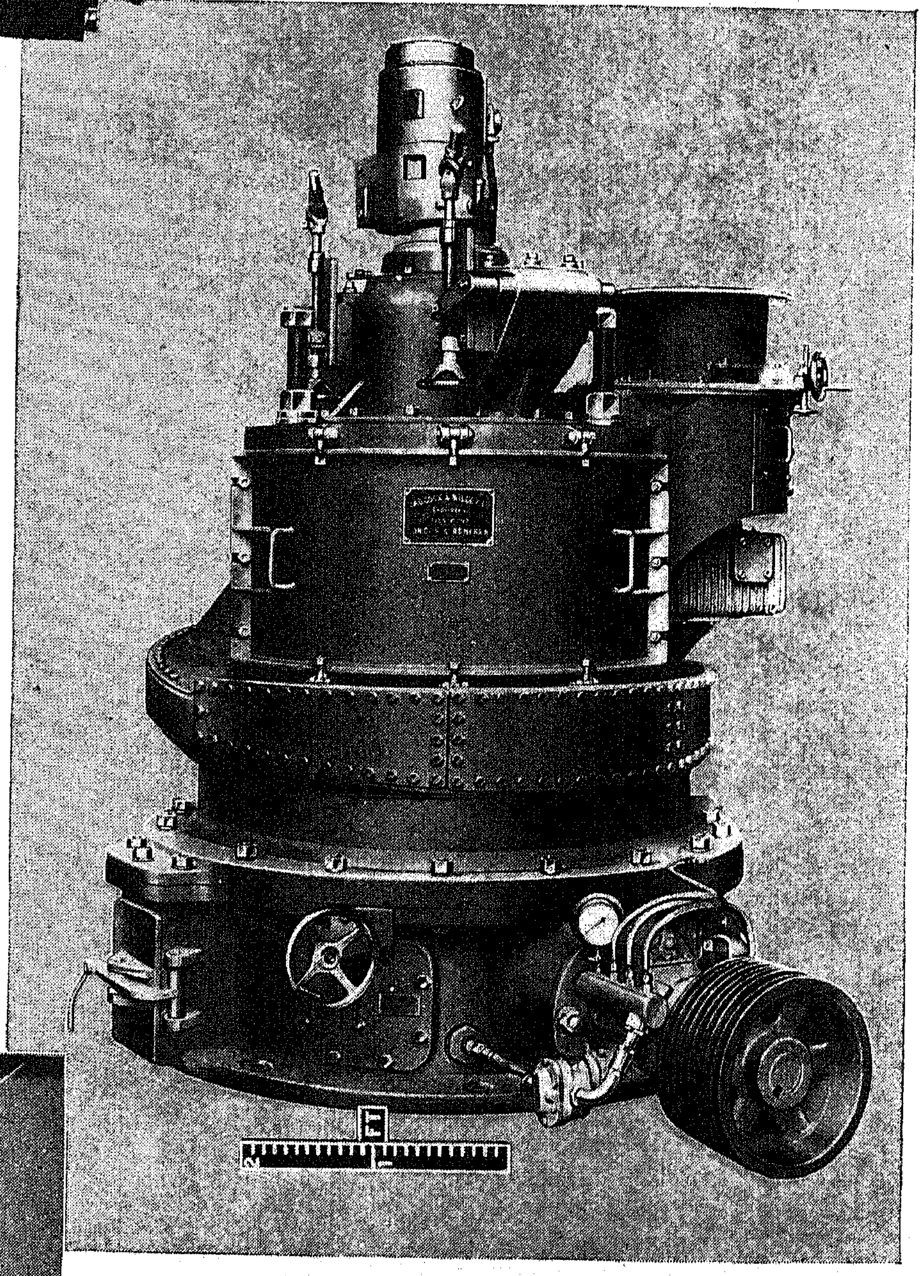

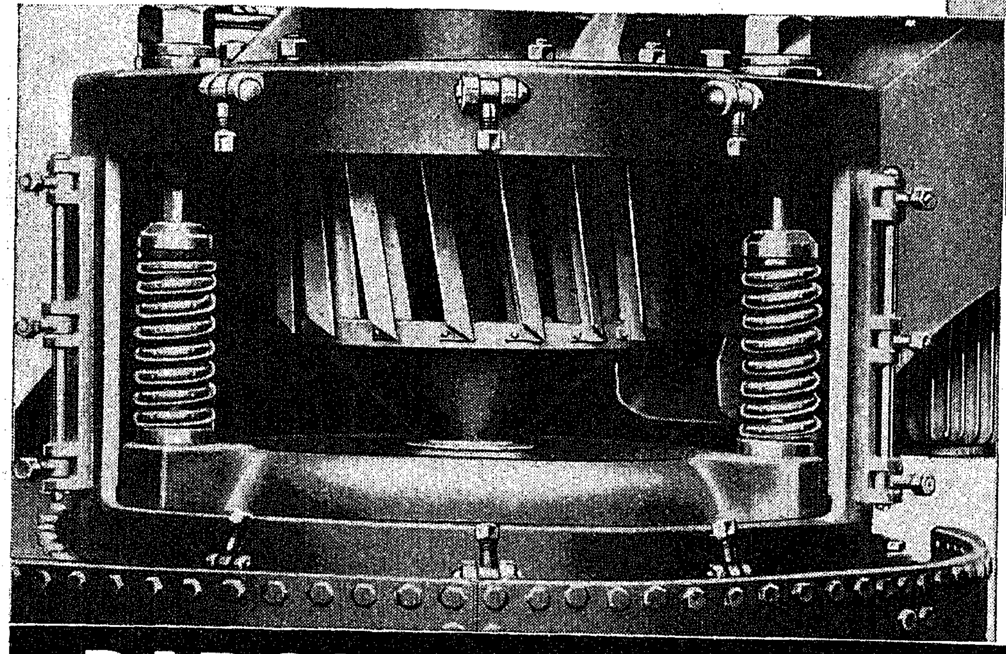

The illustrations show:

TOP. Grinding element of B. & W. Type "E" Mill.

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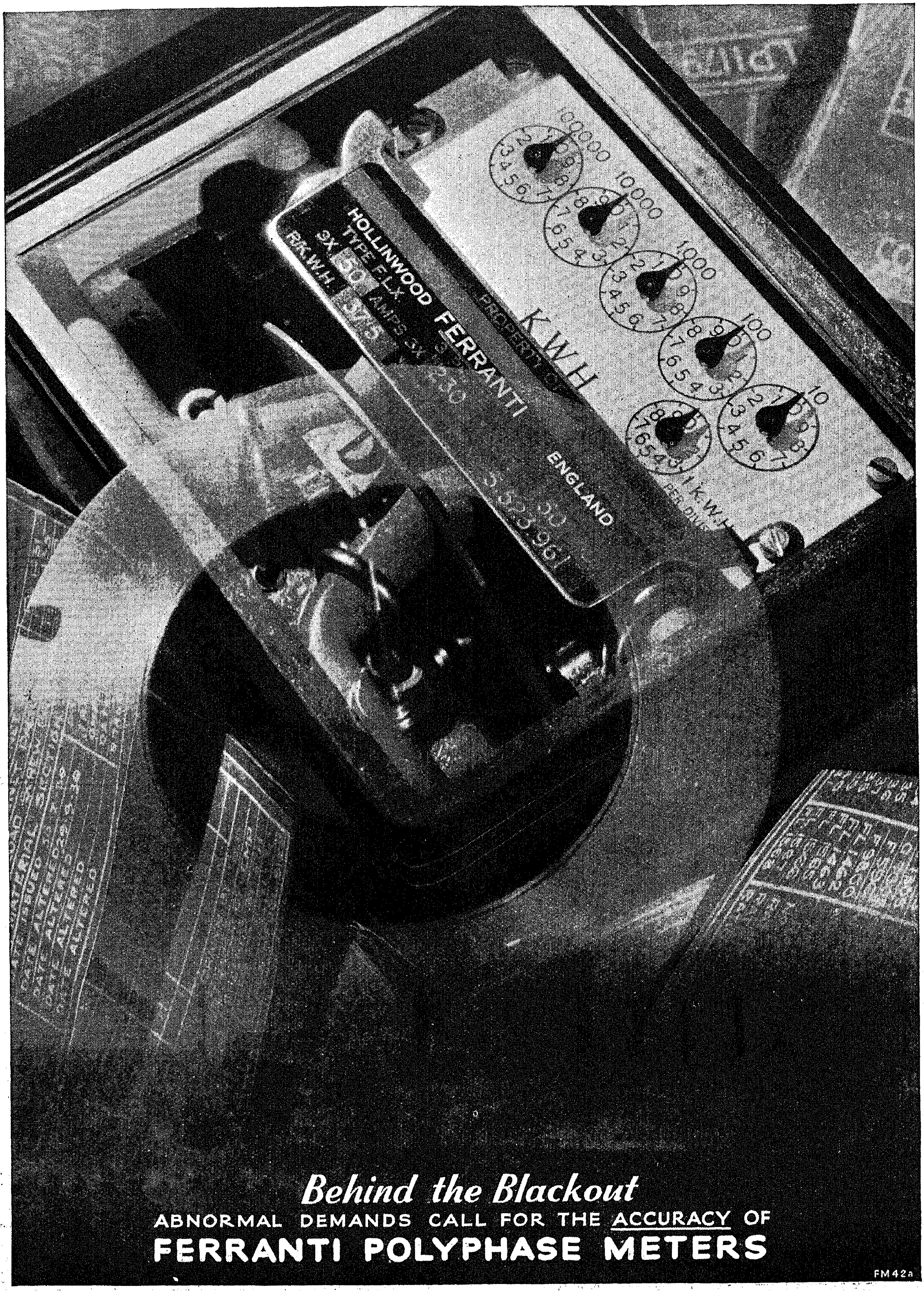
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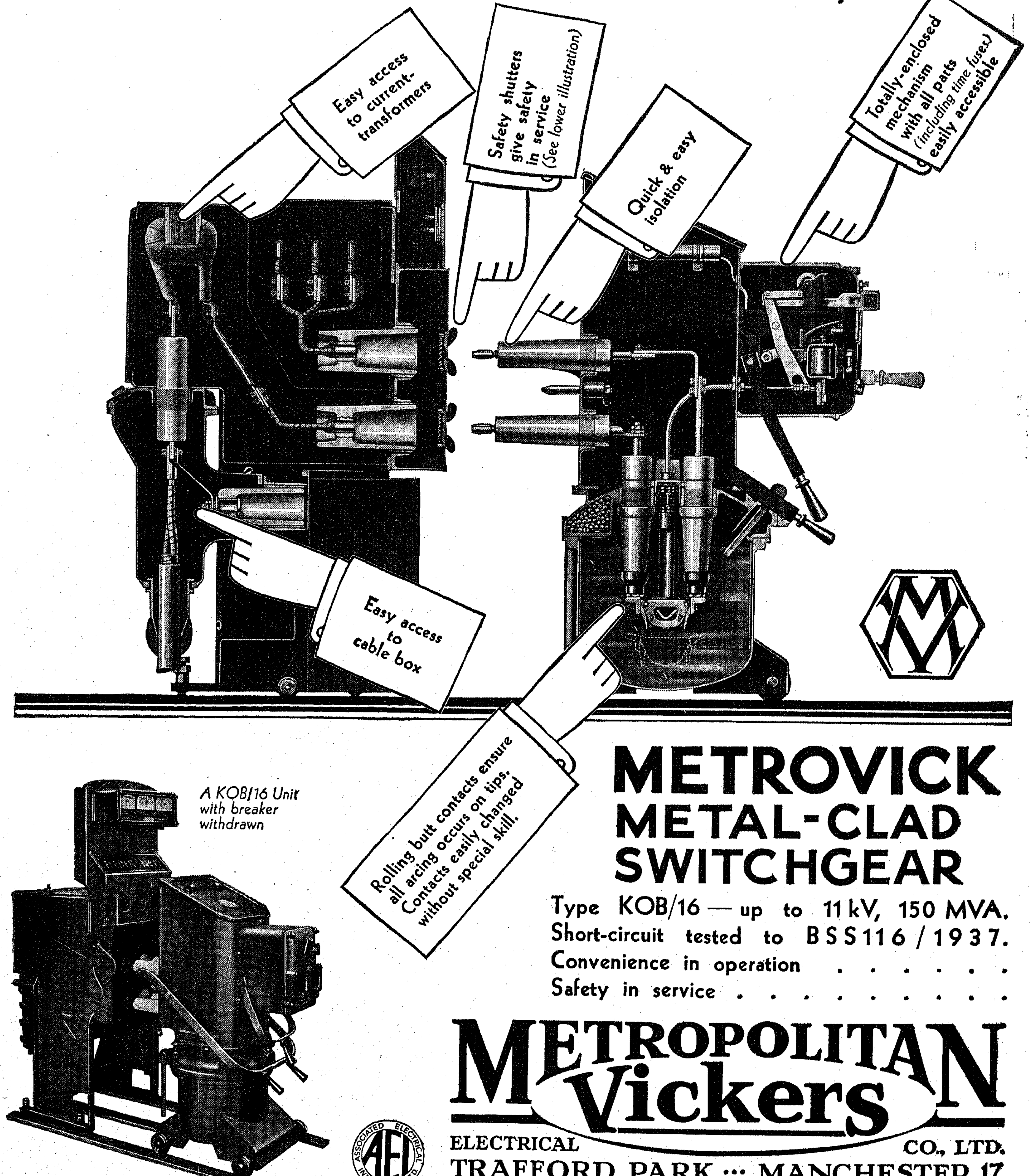
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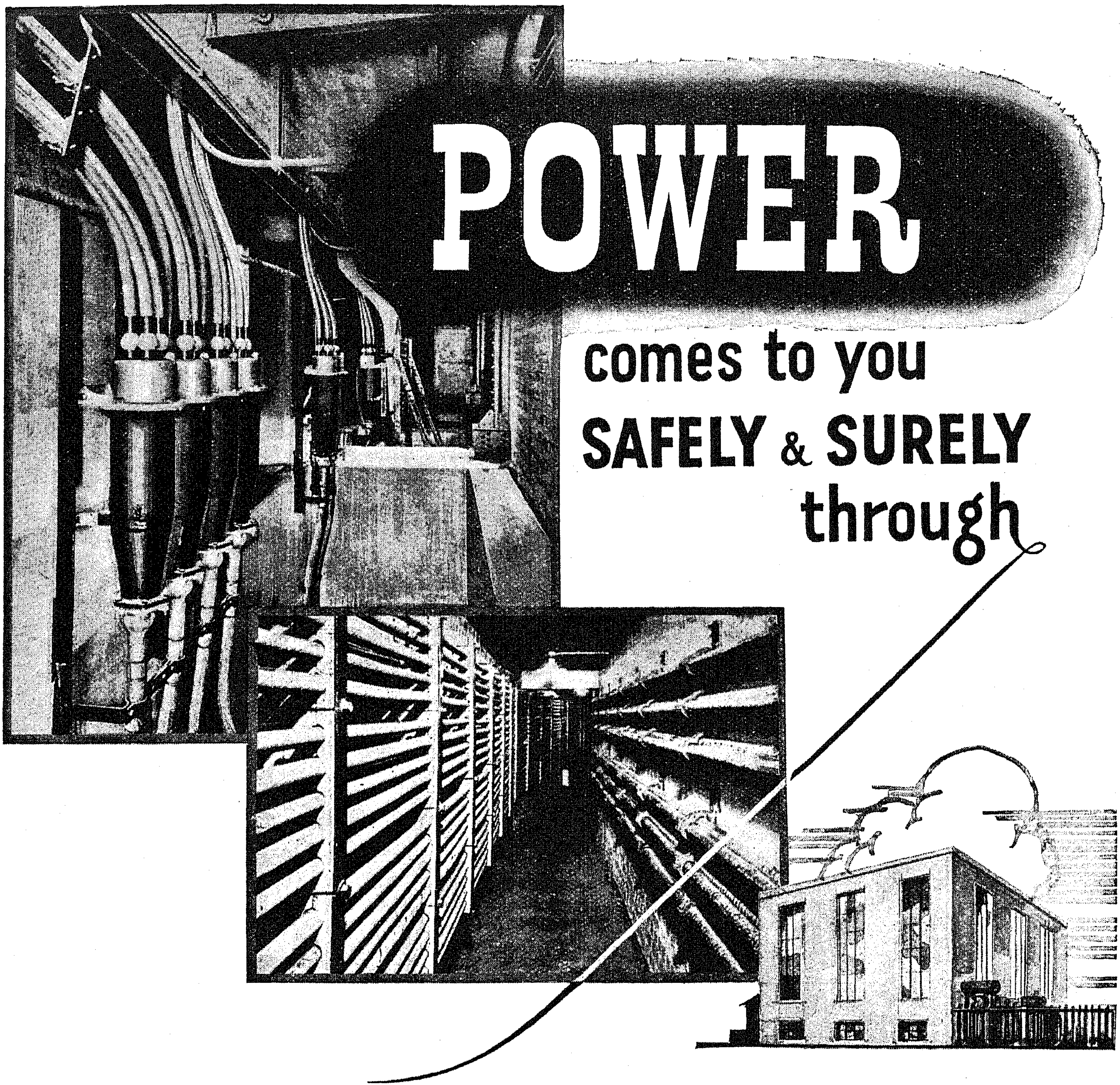

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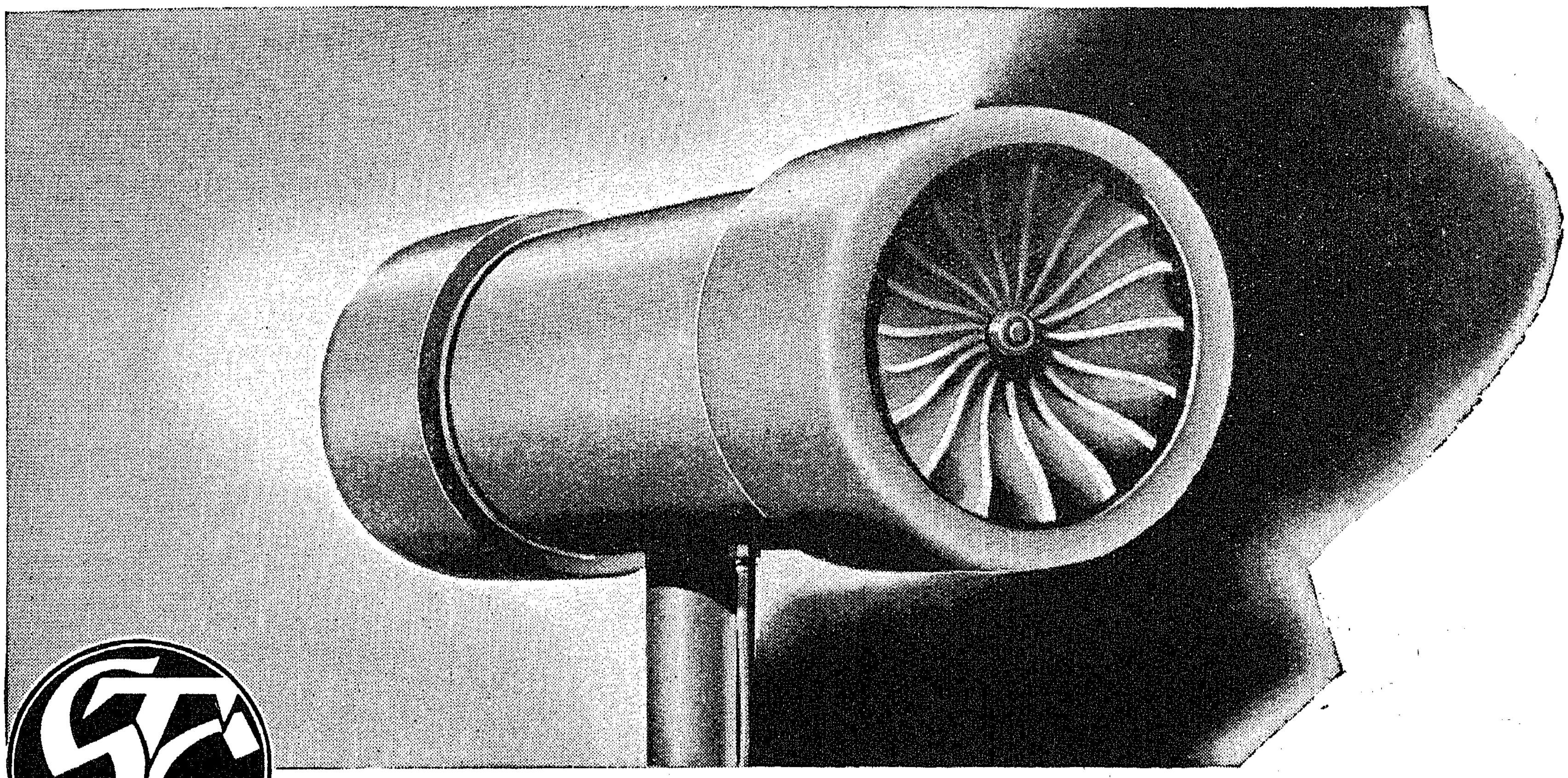

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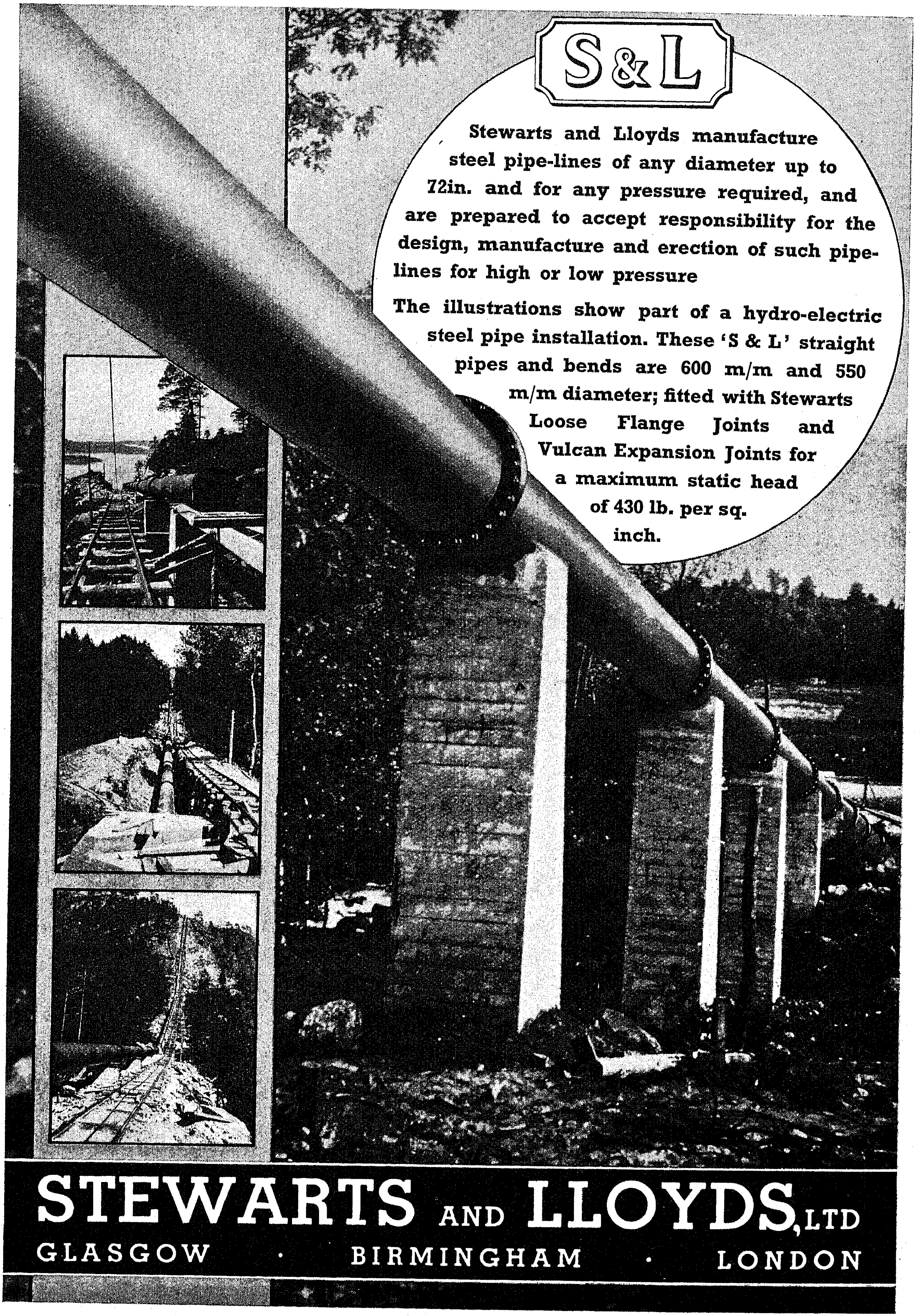

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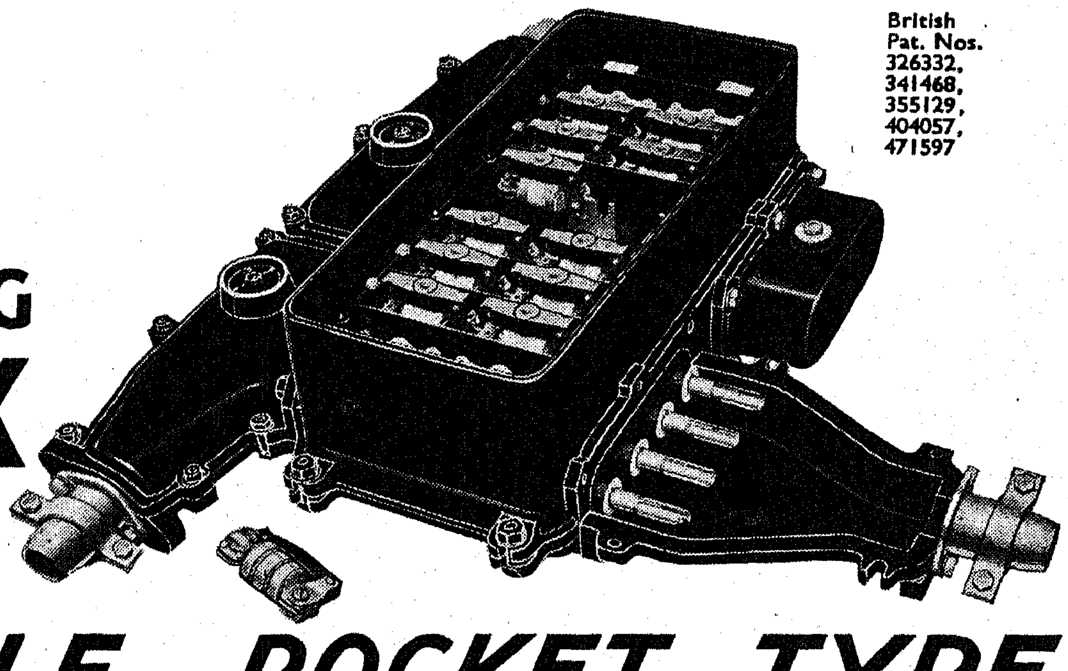

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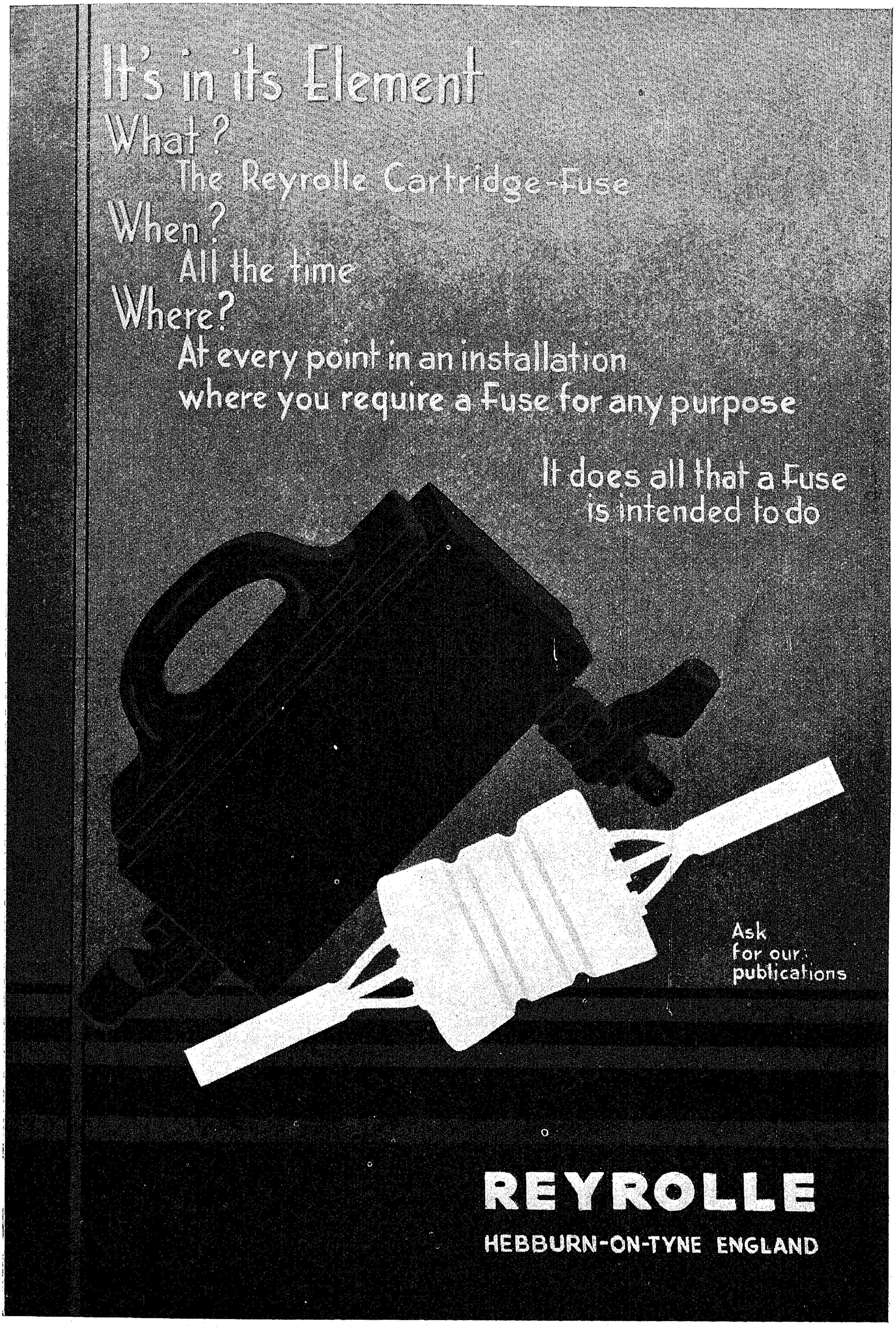
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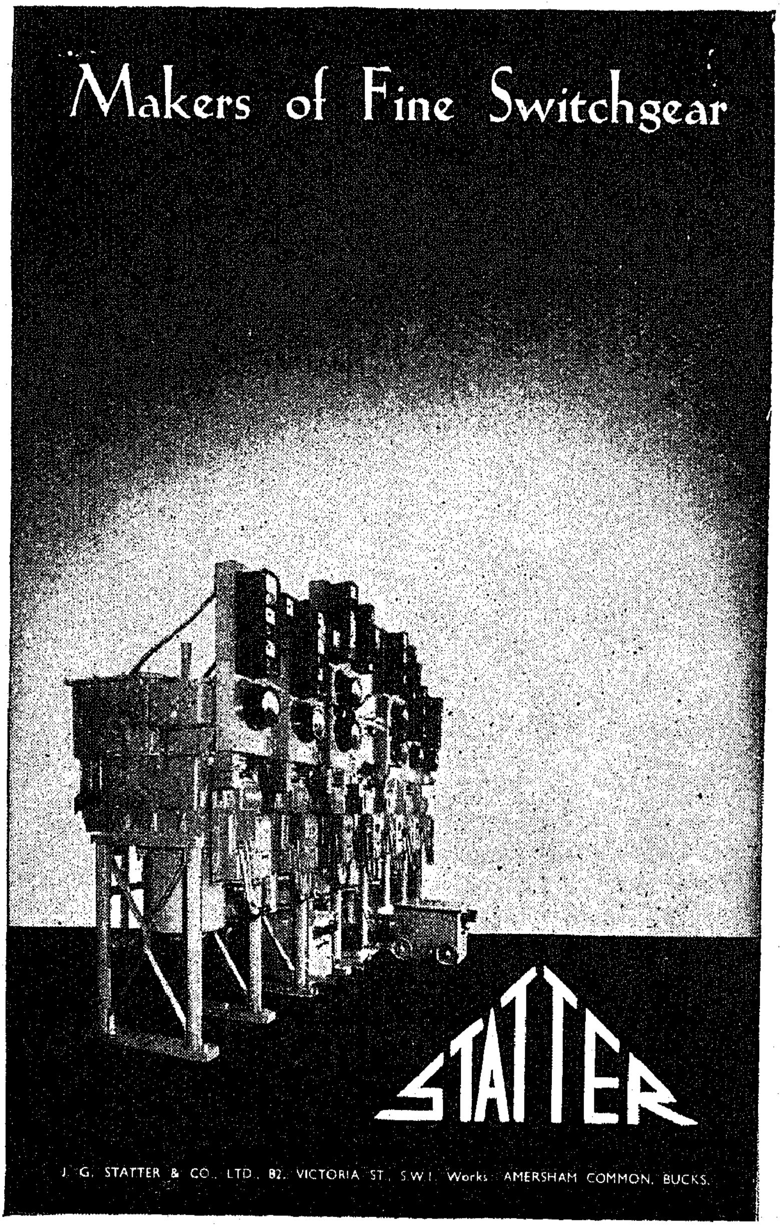

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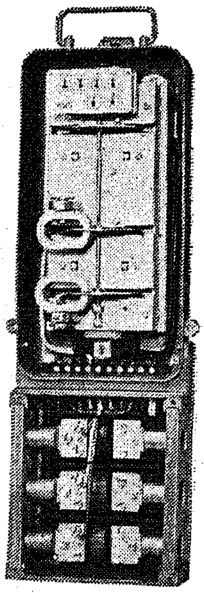

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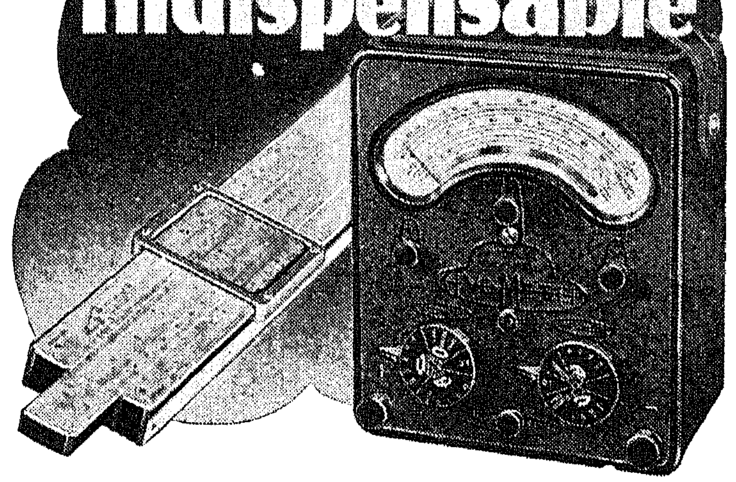

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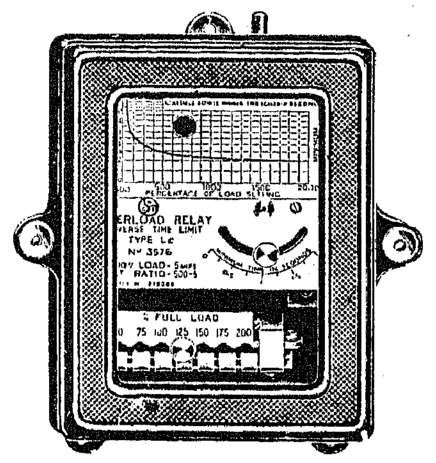

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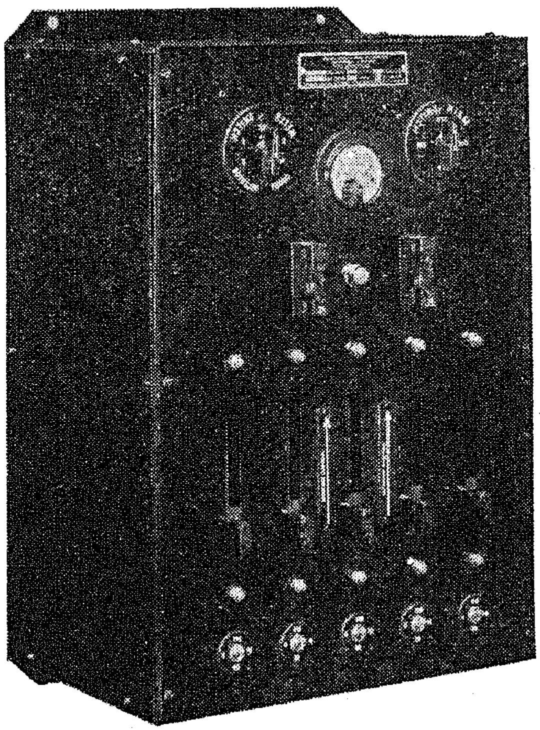

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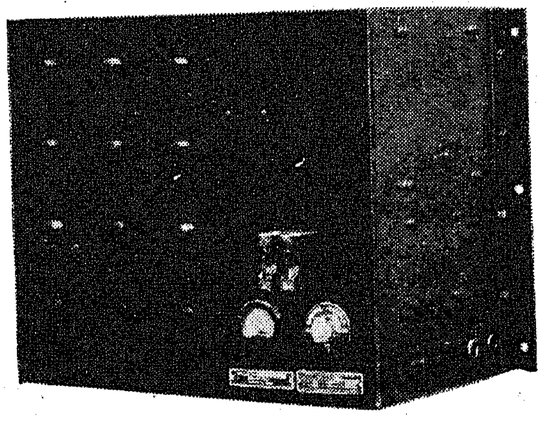

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